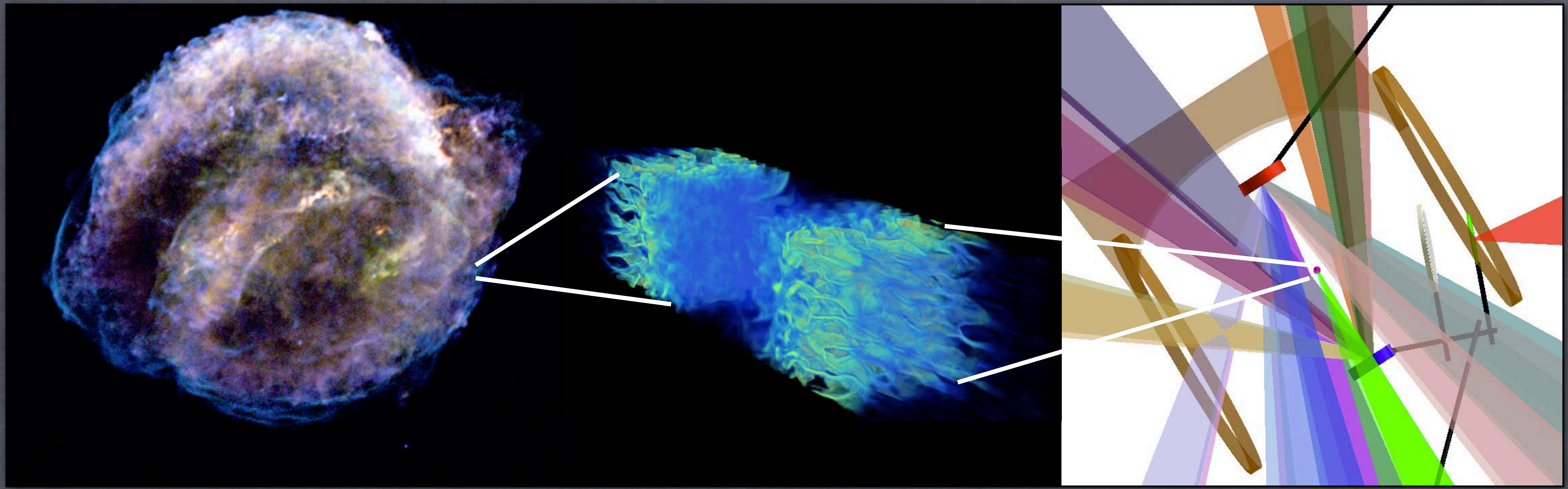


Universe ⟷ microphysics ⟷ experiments

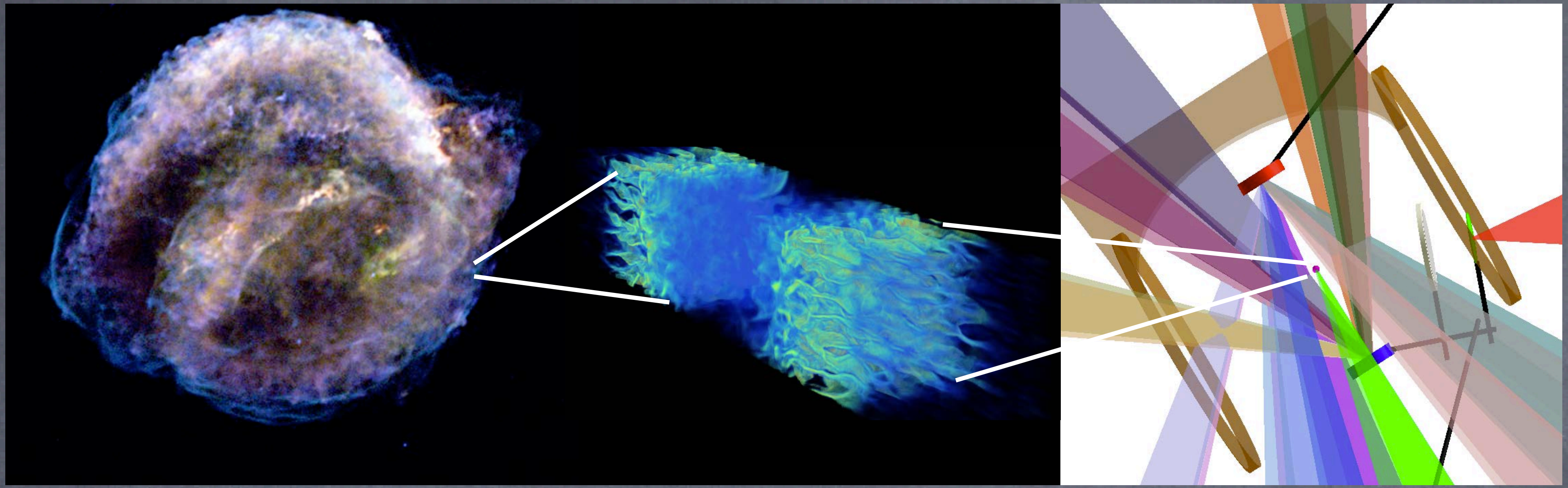
Prospects for collisionless shocks experiments on NIF

•**<u>Purpose:</u>**

- **Create collisionless shocks by counter-streaming plasmas from laser driven ablation to study the physics of astrophysical collisionless shocks relevant to magnetic field generation and cosmic-ray particle acceleration.**

Anatoly Spitkovsky (Princeton)
for ACSEL collaboration

Colliding beam experiments on Omega Laser

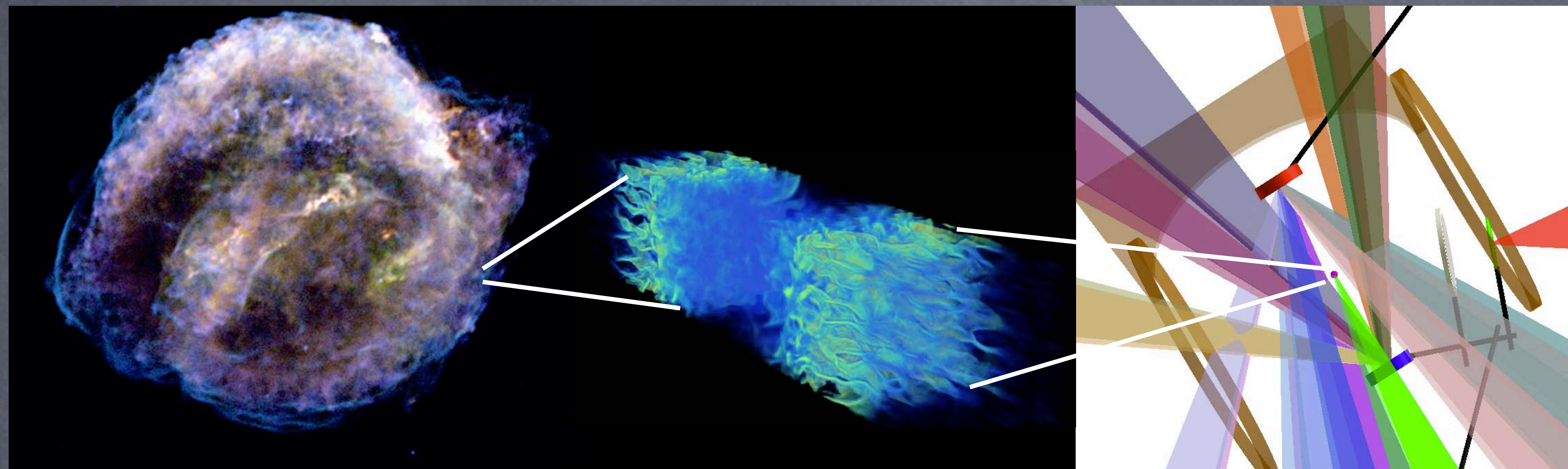


ACSEL coll. (Astrophysical Collisionless Shock Experiments with Lasers)

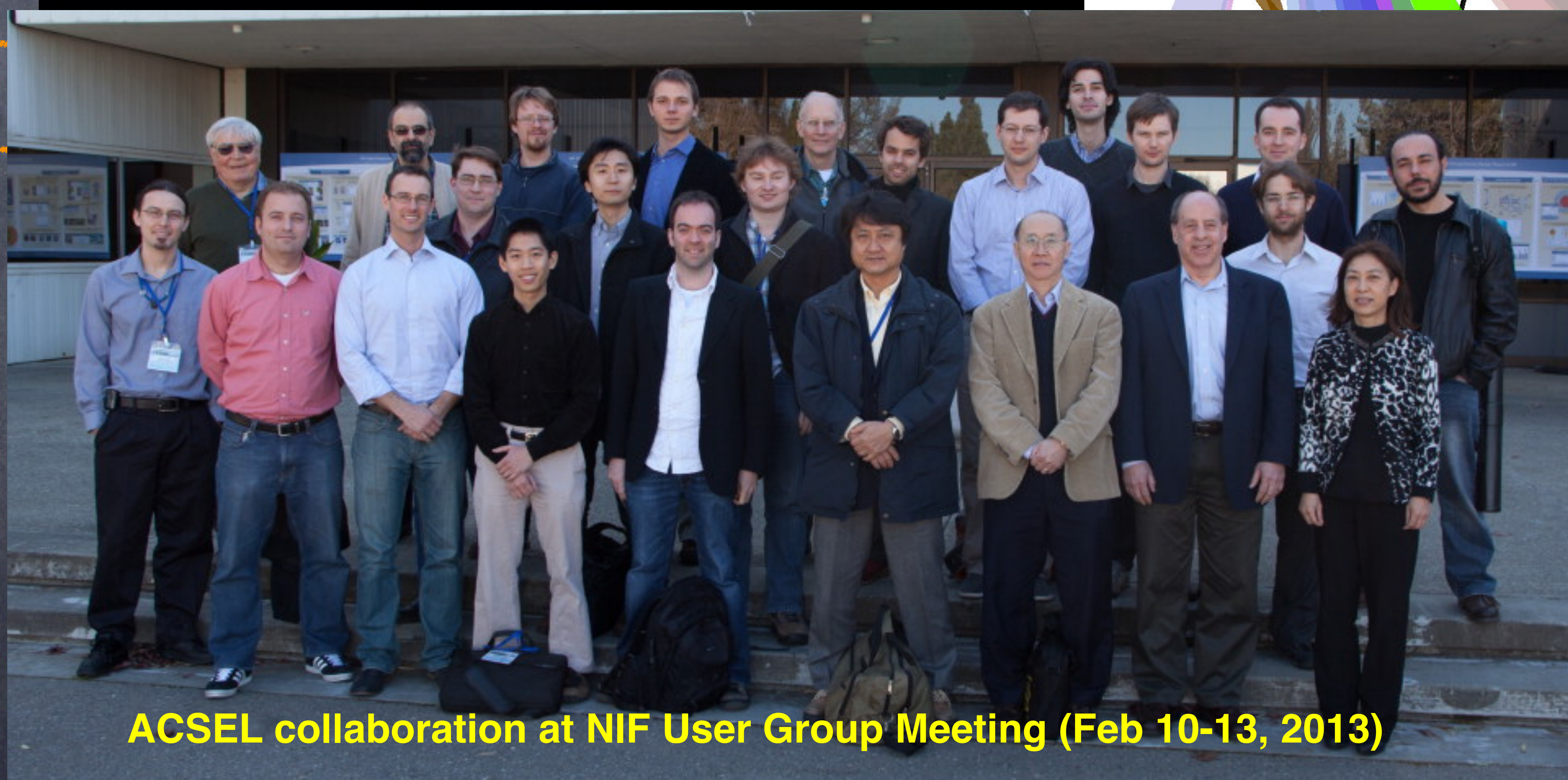
LLNL: C. Huntington, H.-S. Park, M. Levy, C. Plechaty, D. Ryutov, B. Remington, S. Ross
Princeton University: A. Spitkovsky, D. Caprioli, J. Park
LLE, Rochester: G. Fiksel, D. Barnak, P.-Y. Chang, D. Froula
MIT: R. Petrasso, A. Zylstra, C-K. Li
Osaka University: Y. Sakawa, Y. Kuramitsu, T. Morita, H. Takabe
University of Oxford, UK: G. Gregori, J. Meinecke, A. Bell
ETH Zurich, Switzerland: F. Miniati; **York University,** UK: N. Woolsey
École Polytechnique, France: M. Koenig, A. Ravasio, A. Pelka, R. Yurchak
Rice University, Houston: E. Liang
University of Michigan, Ann Arbor: R.P. Drake, M. Grosskopf, C. Kuranz, E. Rutter

Goal: create a platform for shock studies on HED laser facilities (scaling to NIF)

Colliding beam experiments on Omega Laser



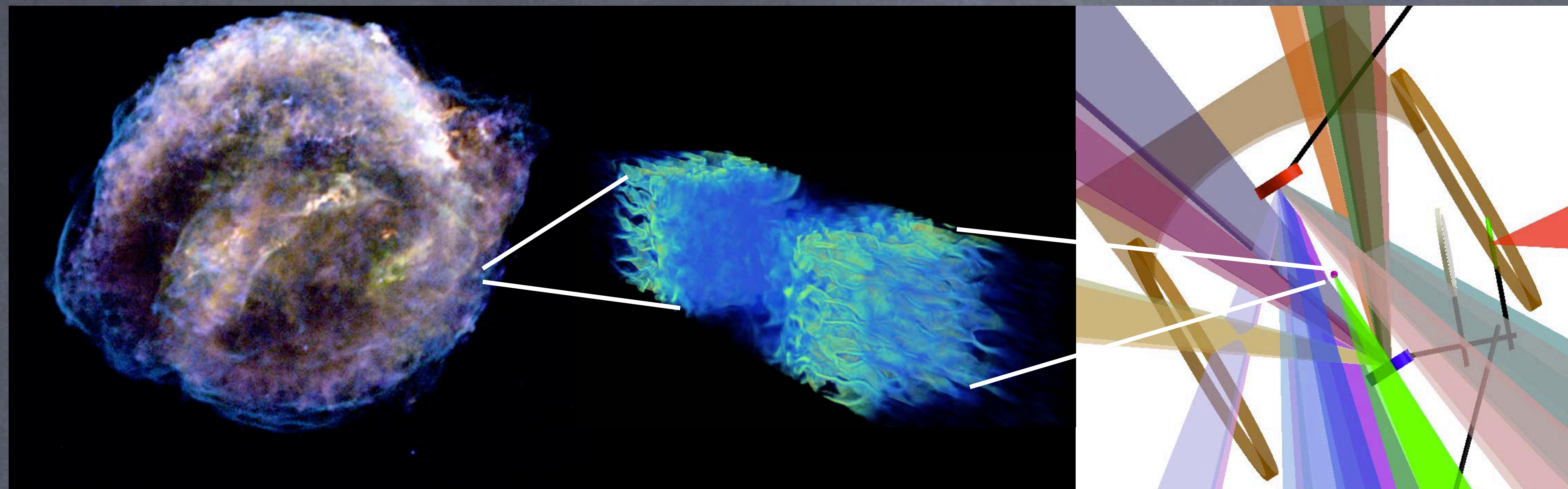
ACSEL ... ith Lasers)



ACSEL collaboration at NIF User Group Meeting (Feb 10-13, 2013)

Goal: create a platform for shock studies on HED laser facilities (scaling to NIF)

Outline



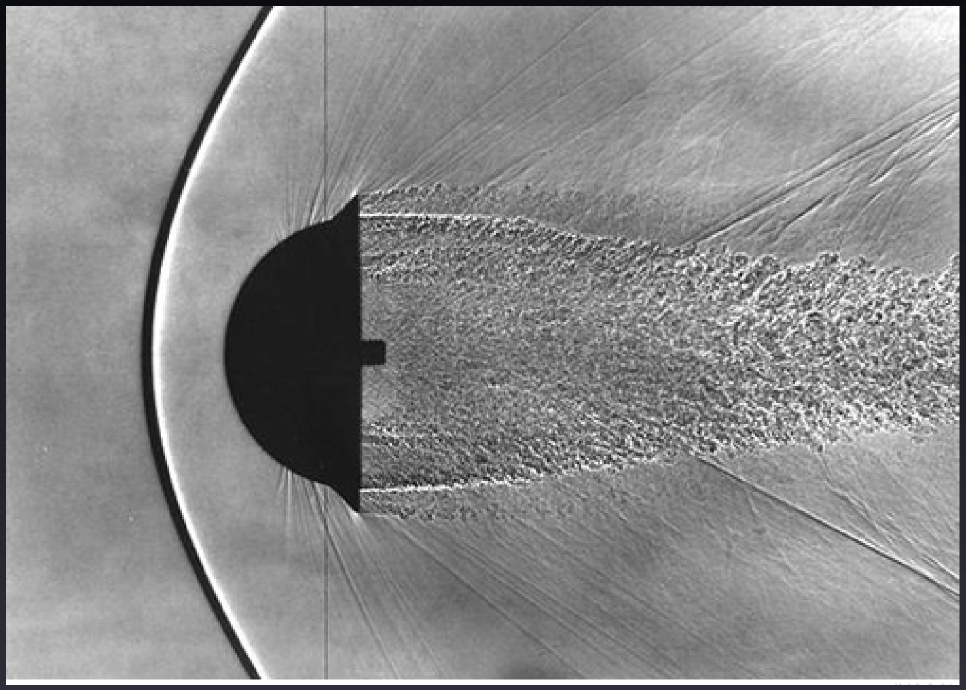
- Introduction to collisionless shocks: open questions
- Shock experiments on Omega: current status
- Scaling to NIF: upcoming experiments and future

What are collisionless shocks?

Shock: sudden change in density, temperature, pressure that decelerates supersonic flow

Thickness ~mean free path
in air: mean free path ~micron

On Earth, most shocks are mediated by collisions



Astro: Mean free path to Coulomb collisions in enormous: 100pc in supernova remnants, ~Mpc in galaxy clusters

Mean free path > scales of interest

shocks must be mediated without direct collision, but through interaction with collective fields

collisionless shocks

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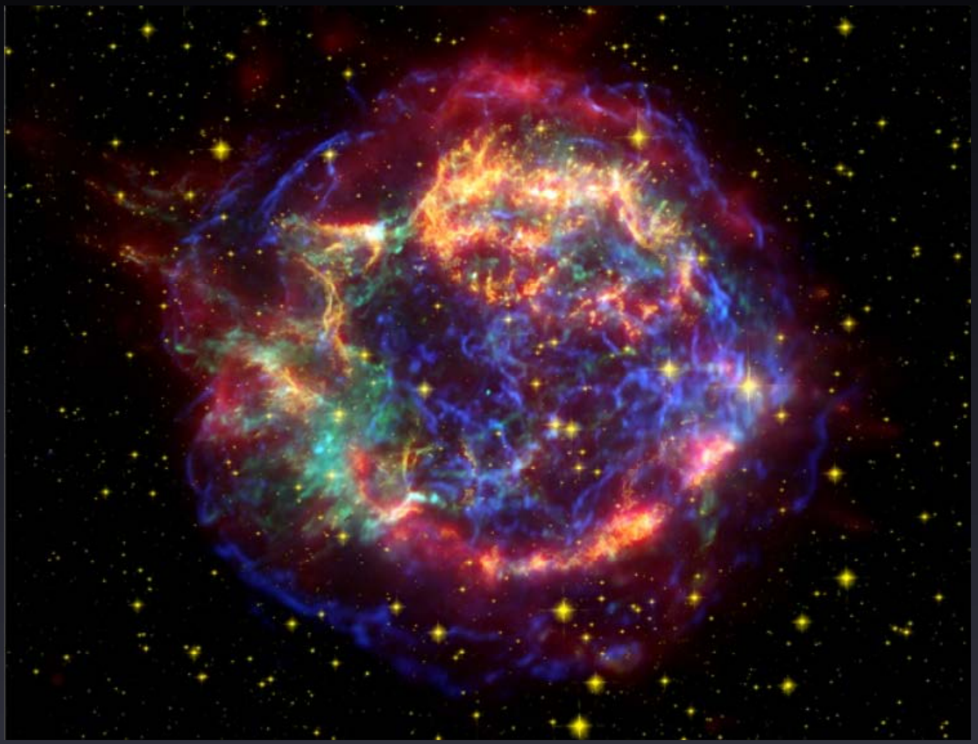
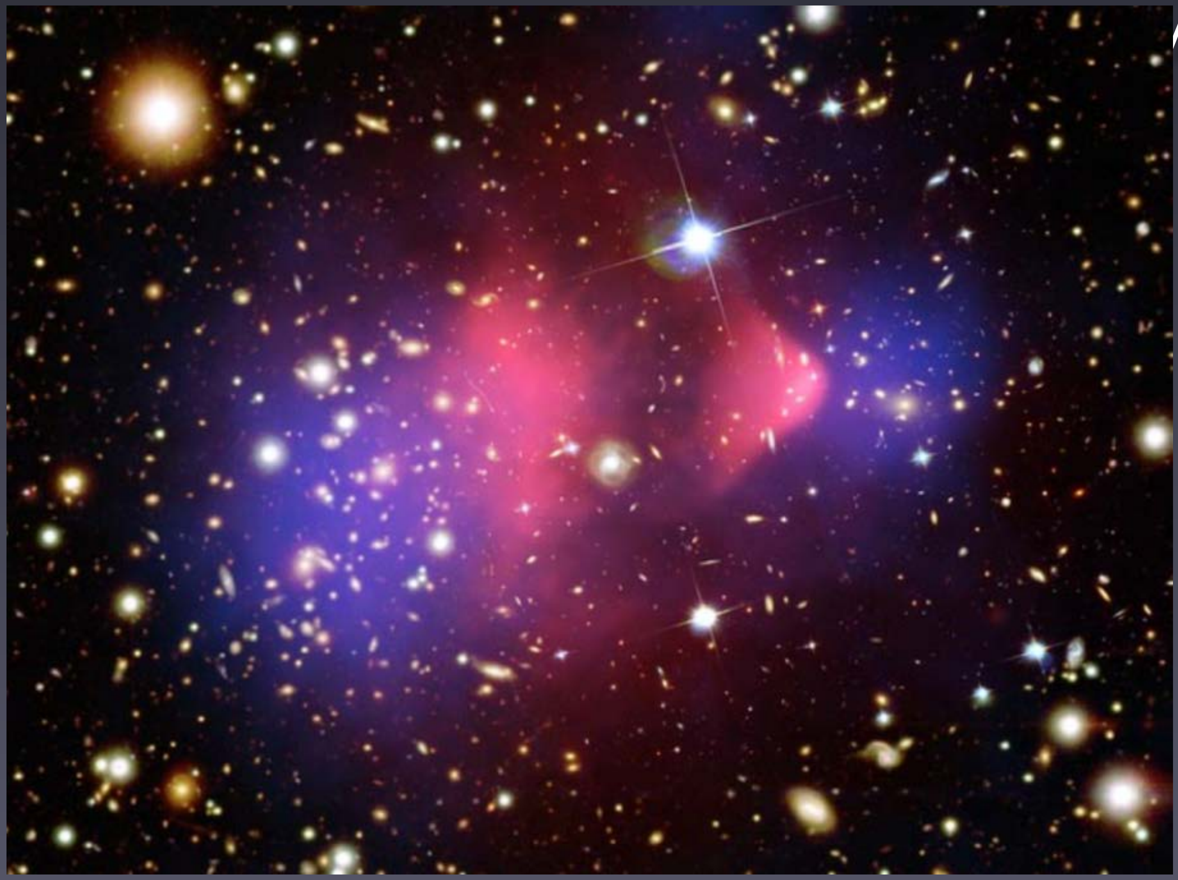




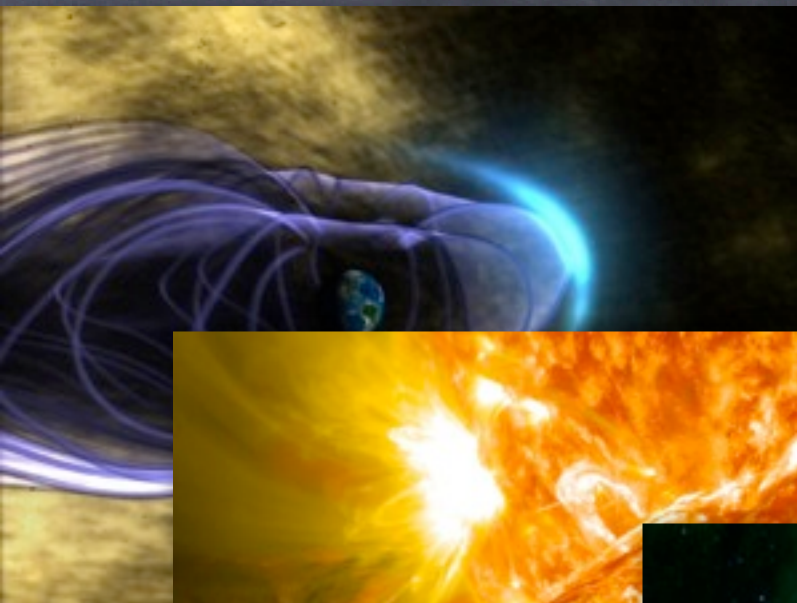
Astro: Mean free path to Coulomb collisions in enormous: 100pc in supernova remnants, ~Mpc in galaxy clusters
Mean free path > scales of interest

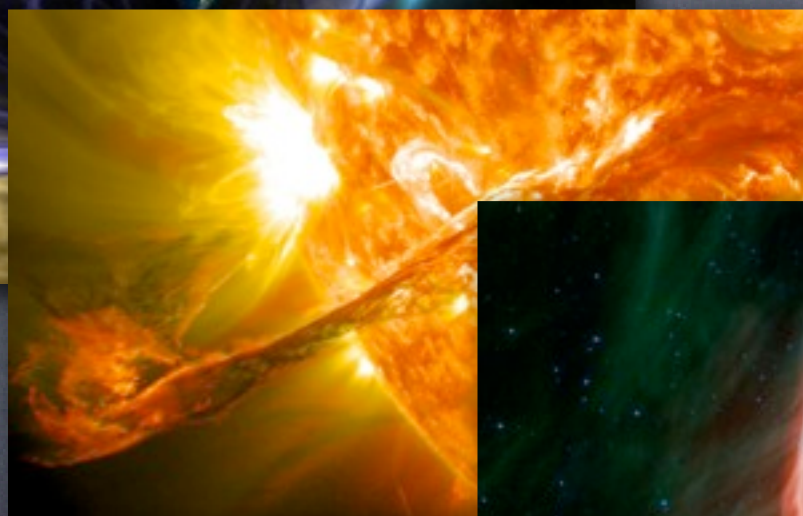
shocks must be mediated without direct collision, but through interaction with collective fields

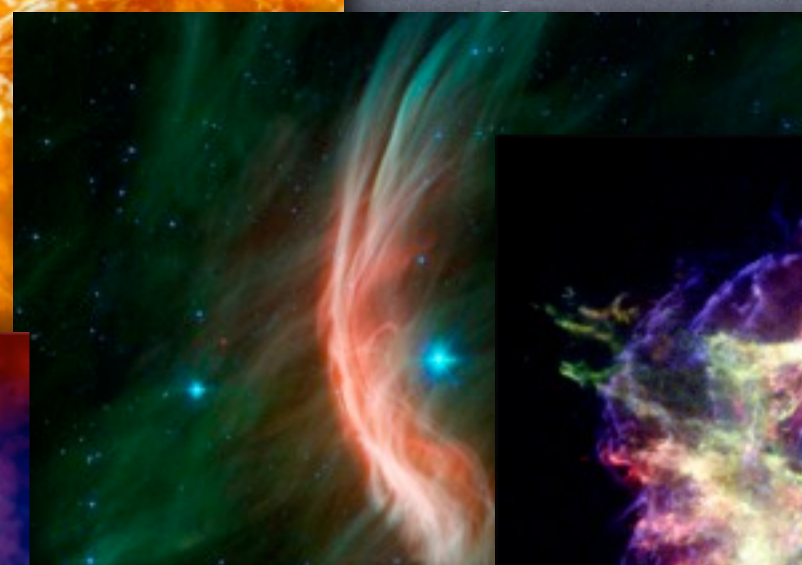
collisionless shocks

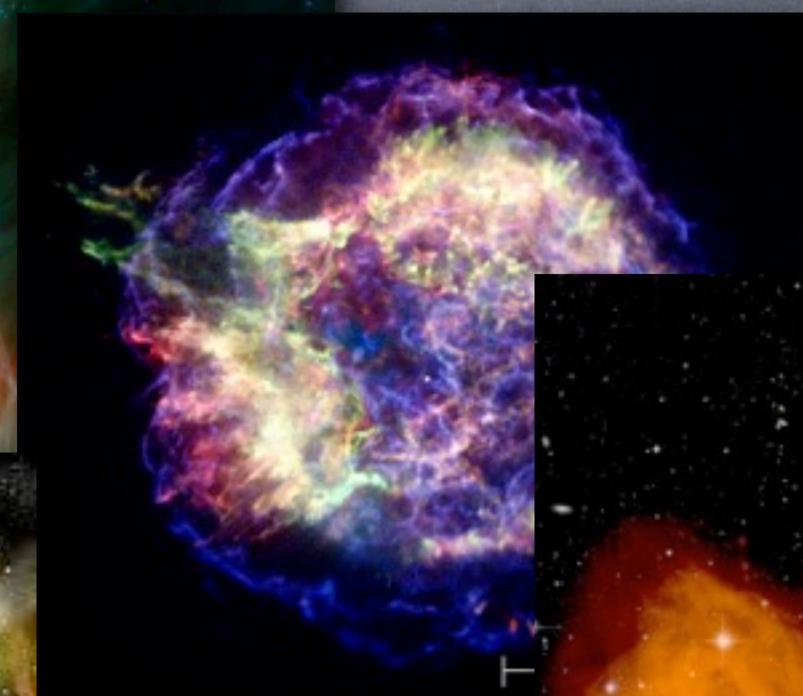
Collisionless shocks in astrophysics

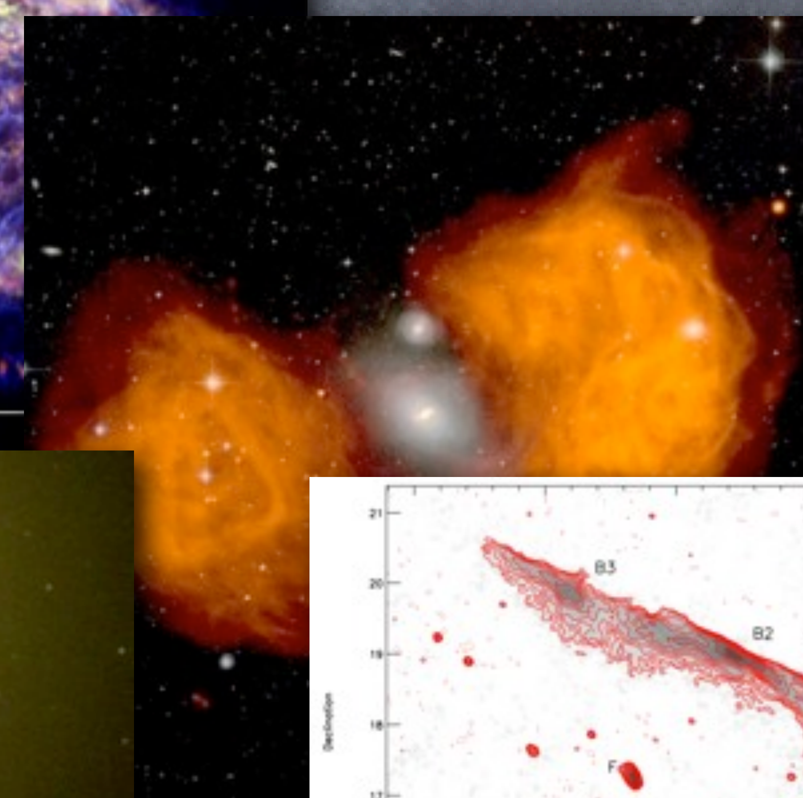
- Supersonic flows are common in Astrophysics
- Mediated by collective electromagnetic interactions
- Sources of accelerated particles, non-thermal emission, and magnetic fields

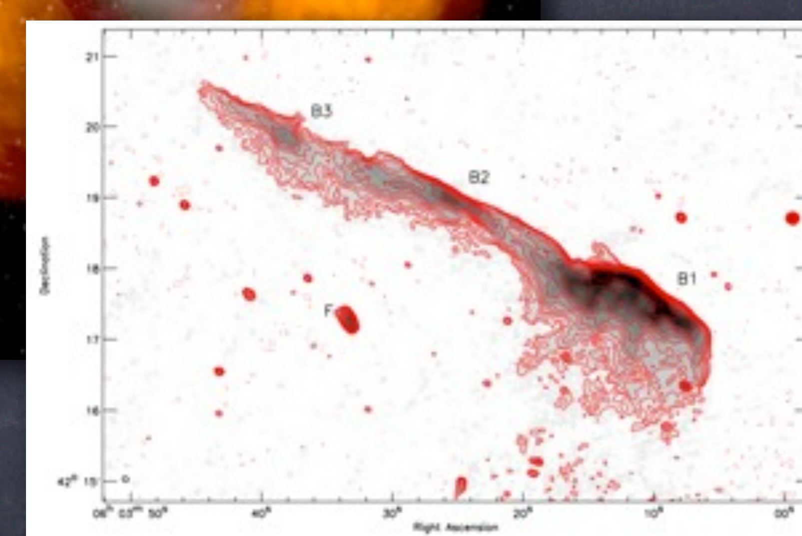




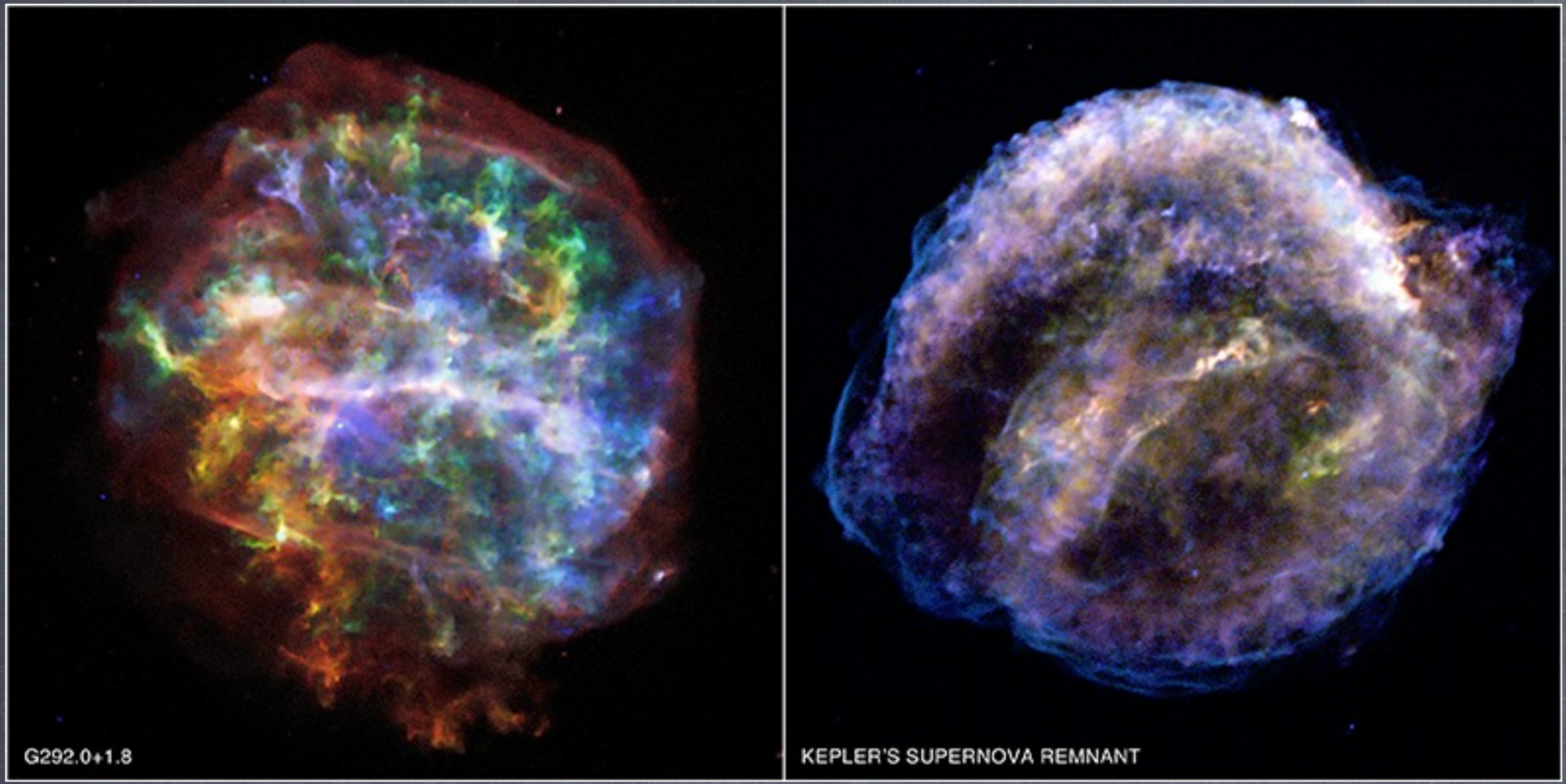


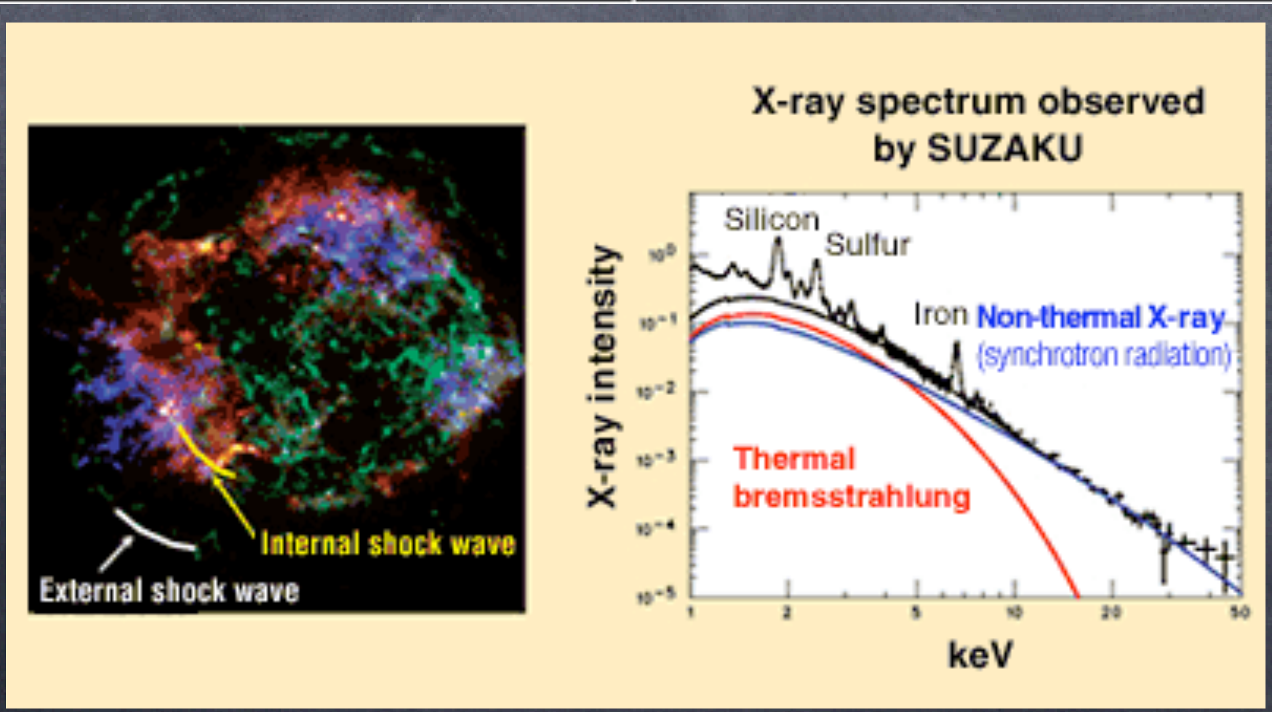




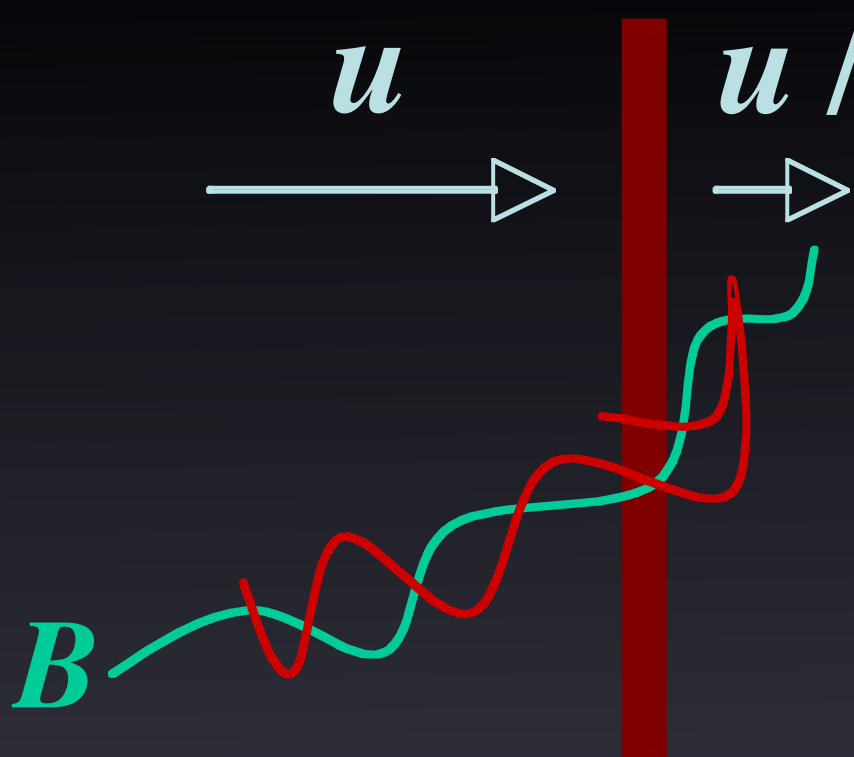


Sources of nonthermal radiation: SNRs



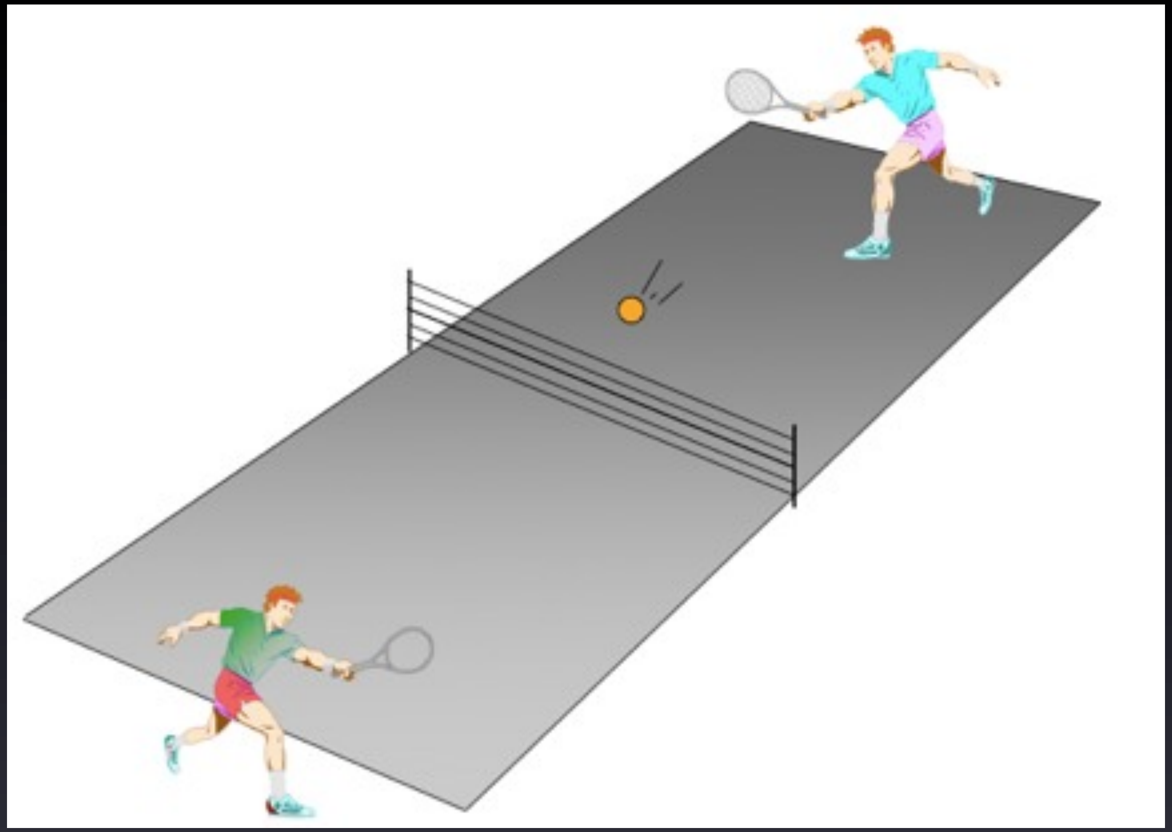


Particle acceleration in shocks:



$\Delta E/E \sim v_{shock}/c$

$N(E) \sim N_0\, E^{-K(r)}$

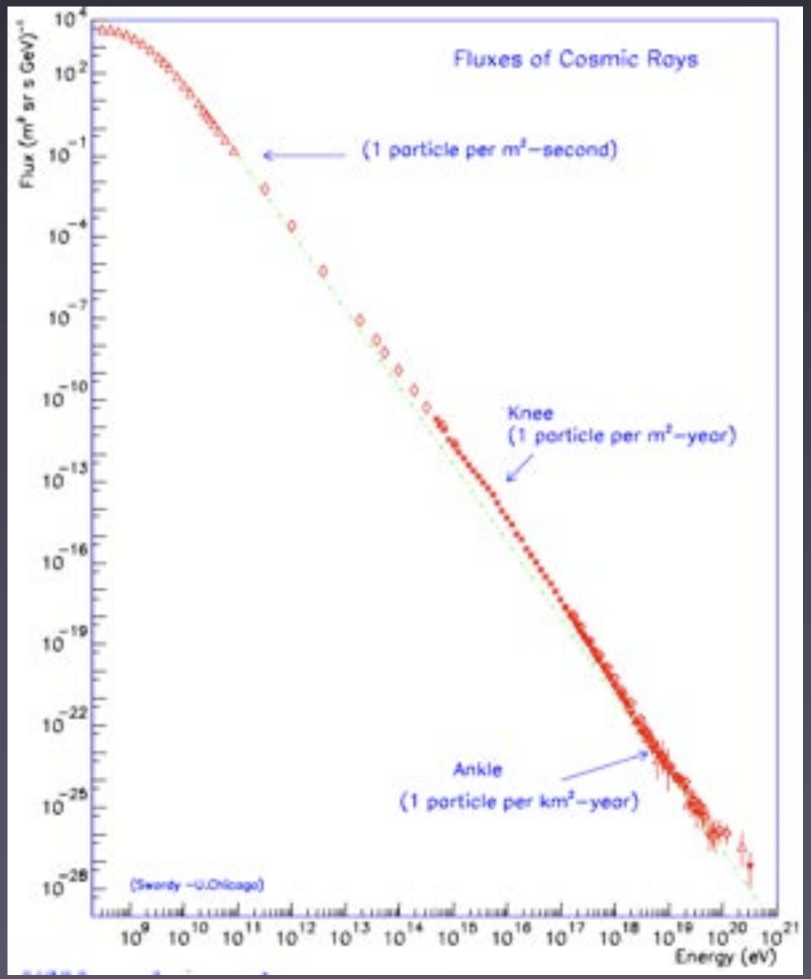


Free energy: converging flows

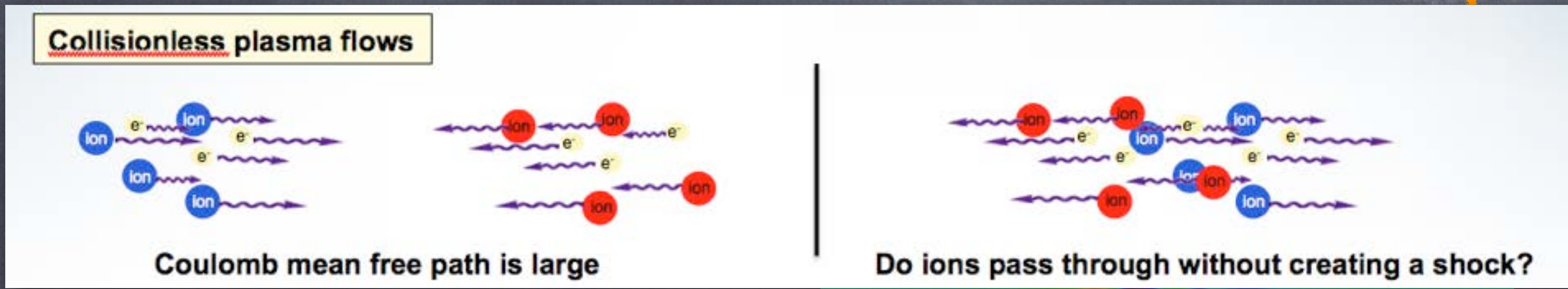
- Original idea -- Fermi (1949) -- scattering off moving clouds. Too slow (second order in v/c) to explain CR spectrum, because clouds both approach *and* recede.

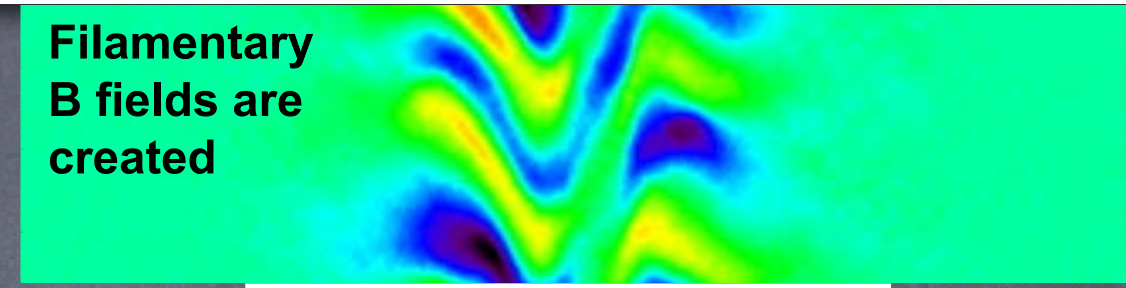
- In shocks, acceleration is first order in v/c, because flows are always converging (Blandford & Ostriker 78,Bell 78, Krymsky 77)

- Efficient scattering of particles is required. Particles diffuse around the shock. Monte Carlo simulations show that this implies very high level of turbulence. Is this realistic? Are there specific conditions?

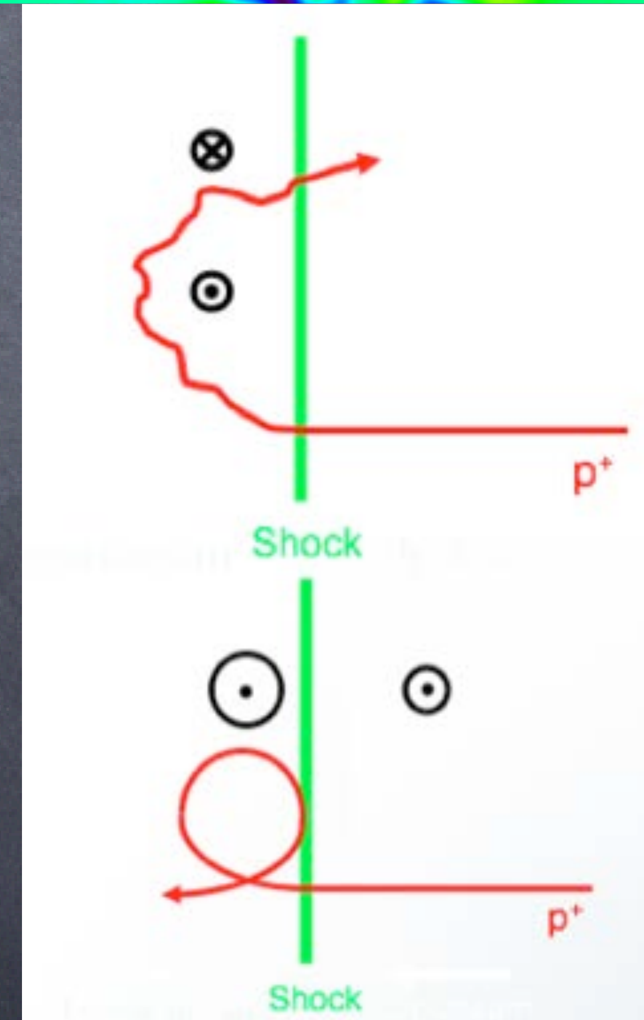


How collisionless shocks work

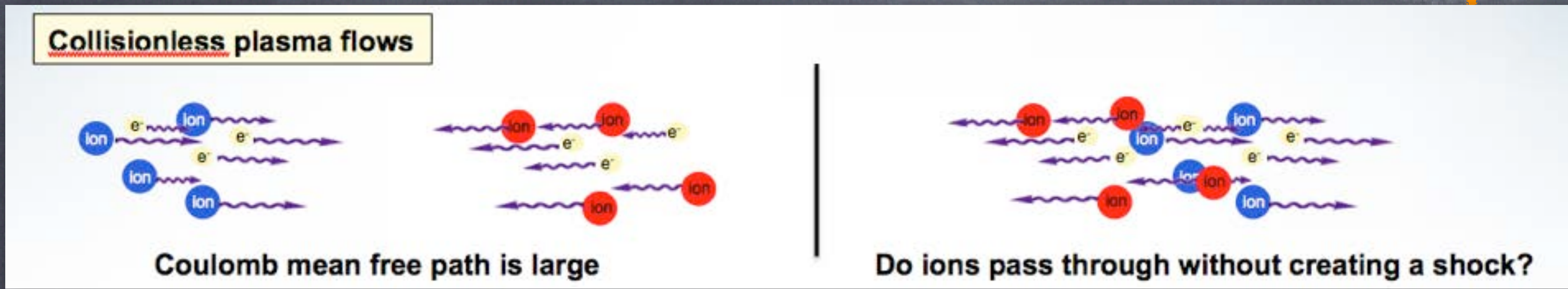




- For low initial B field, particles are deflected by self-generated magnetic fields (filamentation/Weibel instability)
- For large initial B field, particles are deflected by compressed pre-existing fields



How collisionless shocks work



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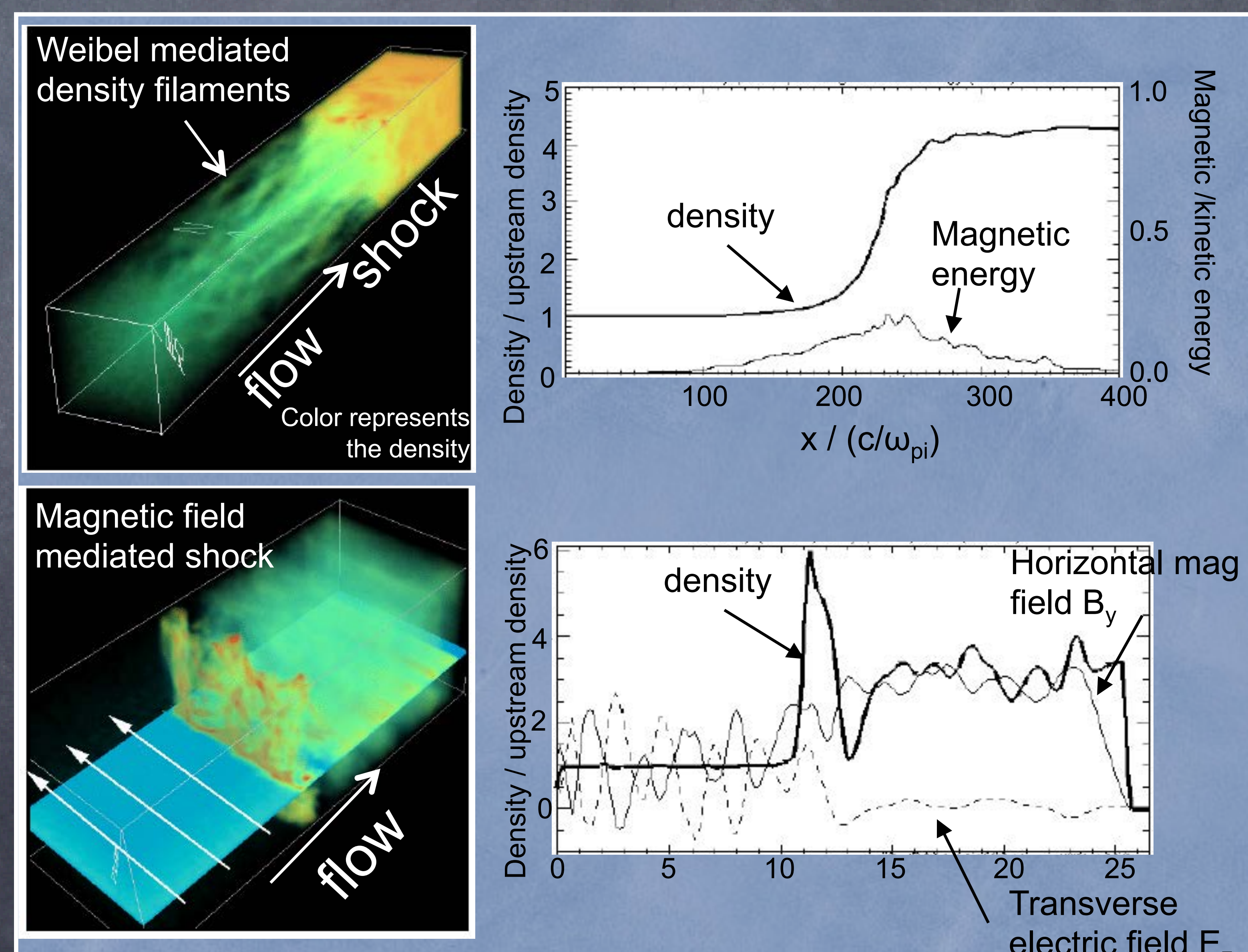
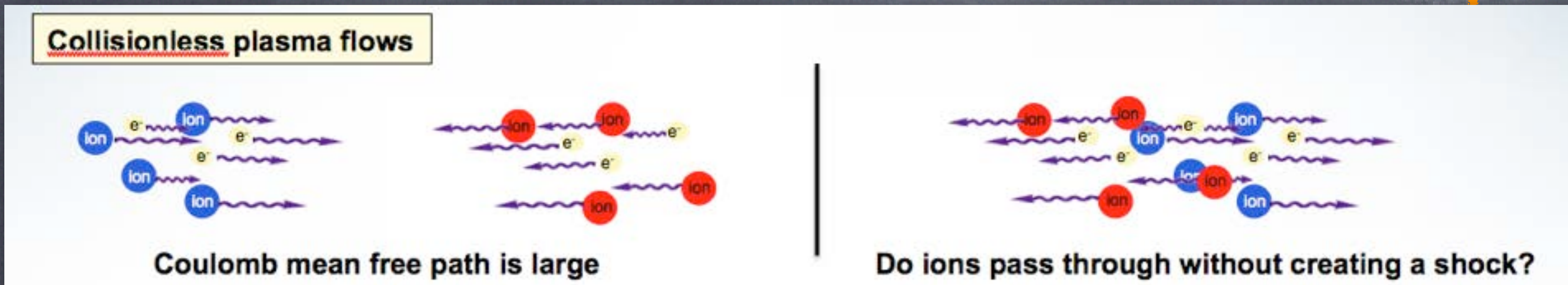
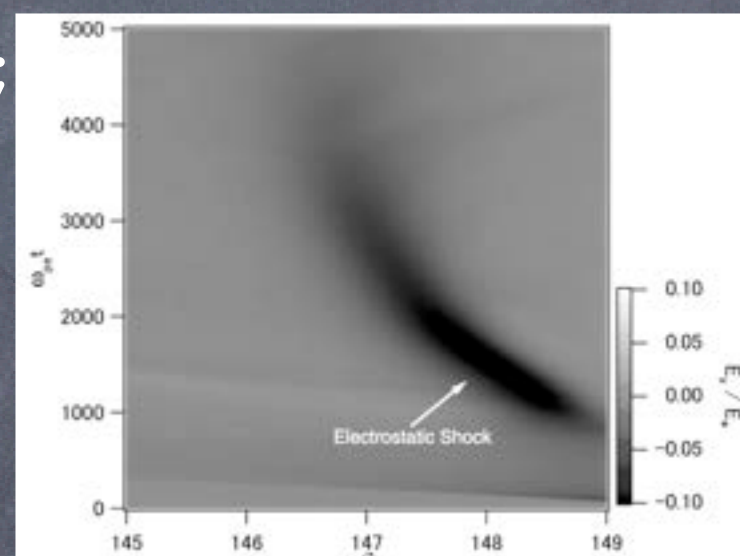
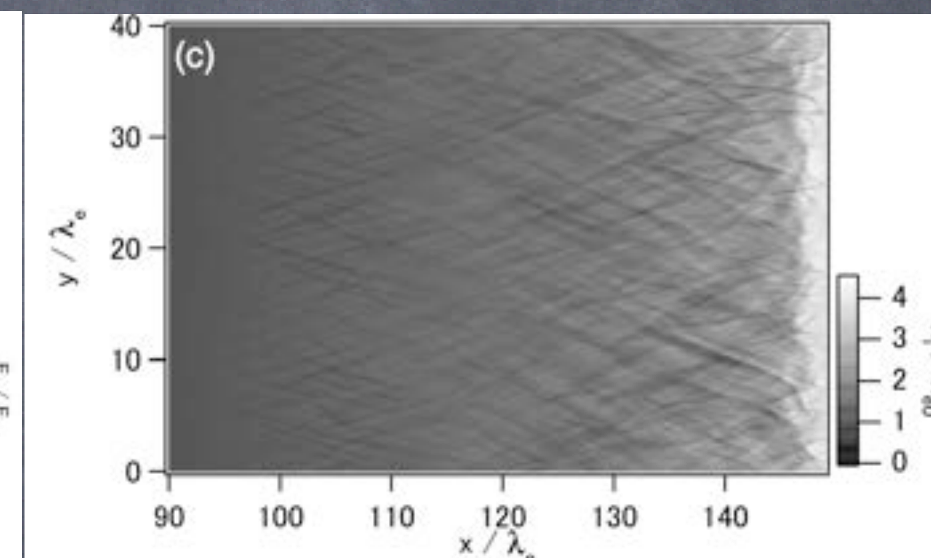


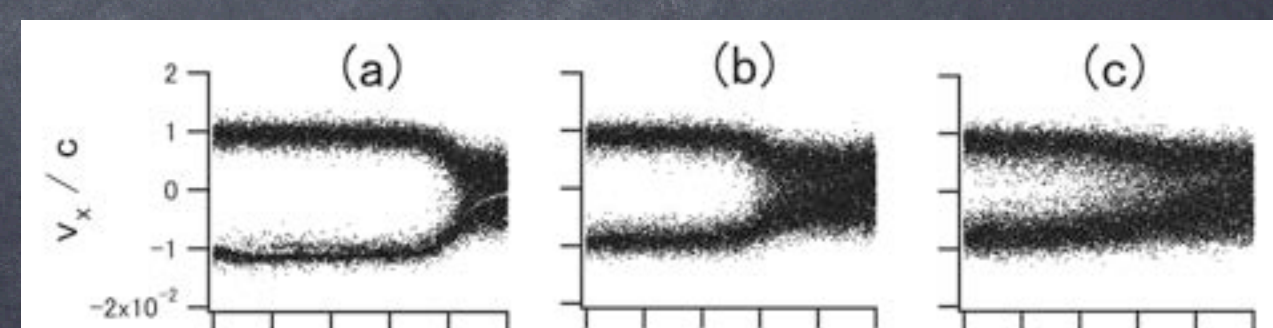
Electrostatic shocks



- Ions are reflected by electrostatic double layer; thickness few electron skin depths
- Works for Te>>Ti plasmas
- Effective Mach numbers are lower than those inferred in astrophysics
- In 2D, electrostatic shocks seem to fade away



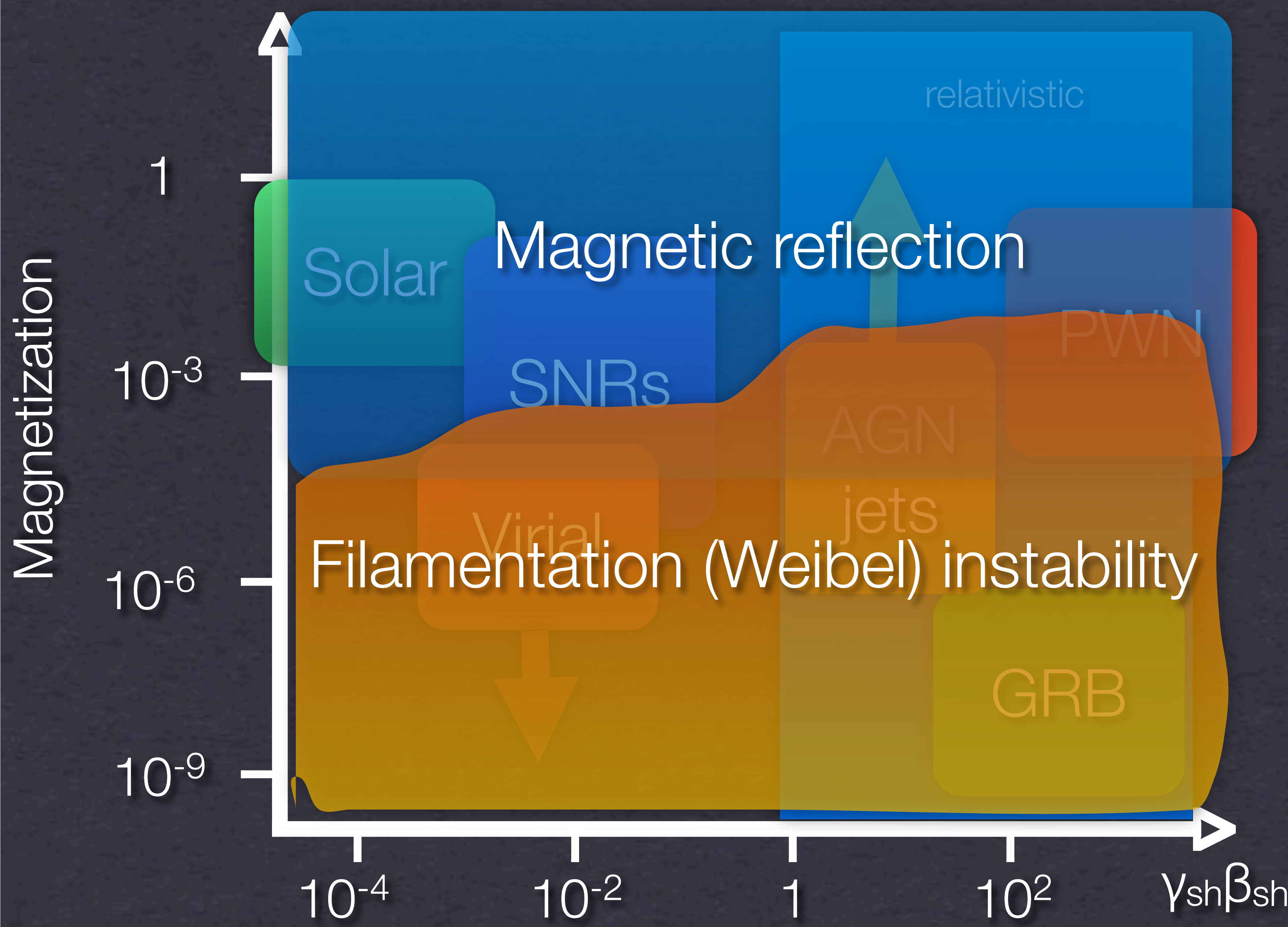


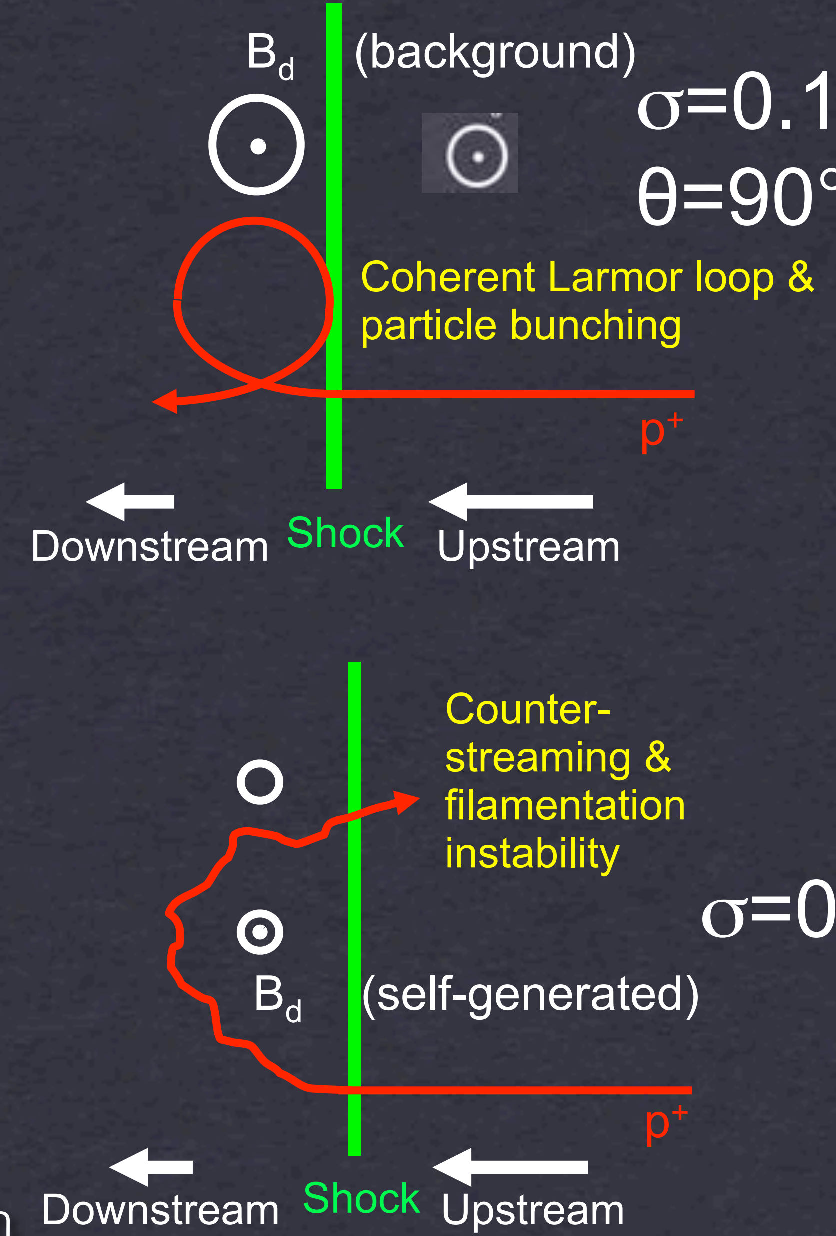


Kato & Takabe 2010

Parameter Space of shocks

$$\sigma \equiv \frac{B^2/4\pi}{(\gamma-1)nmc^2} = \frac{1}{M_A^2} = \left(\frac{\omega_c}{\omega_p}\right)^2\left(\frac{c}{v}\right)^2 = \left[\frac{c/\omega_p}{R_L}\right]^2$$



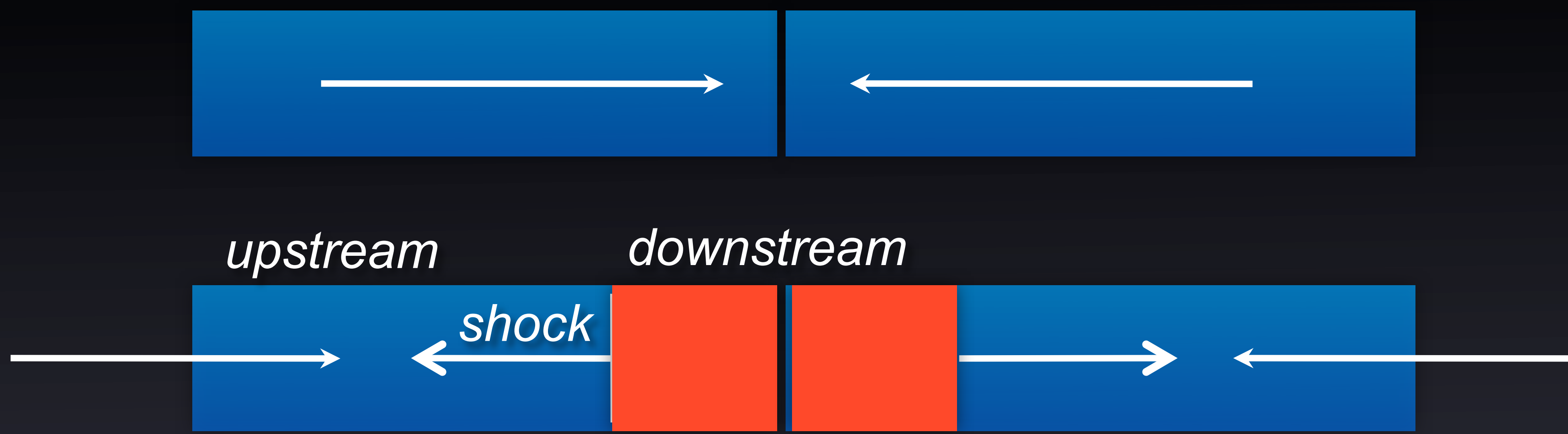


Collisionless shocks: open questions

- What is shock structure and evolution?
- What kind of magnetic turbulence is generated in the shock? Does it survive?
- What is the fraction of particles accelerated at shocks? What does it depend on?

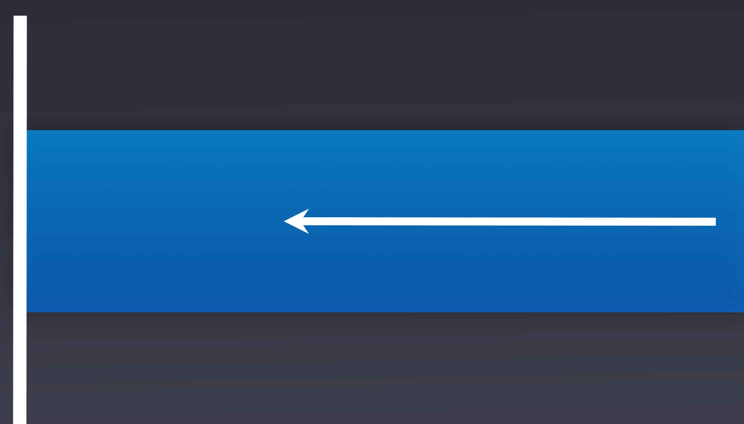
These questions can be answered through simulations, in-situ spacecraft observations of heliospheric shocks, and by laboratory experiments.

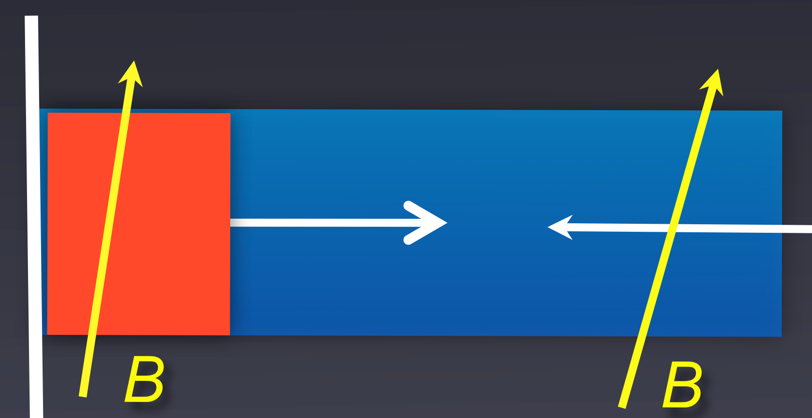
Problem setup: PIC simulations



"Shock" is a jump in density & velocity

Use reflecting wall to initialize a shock



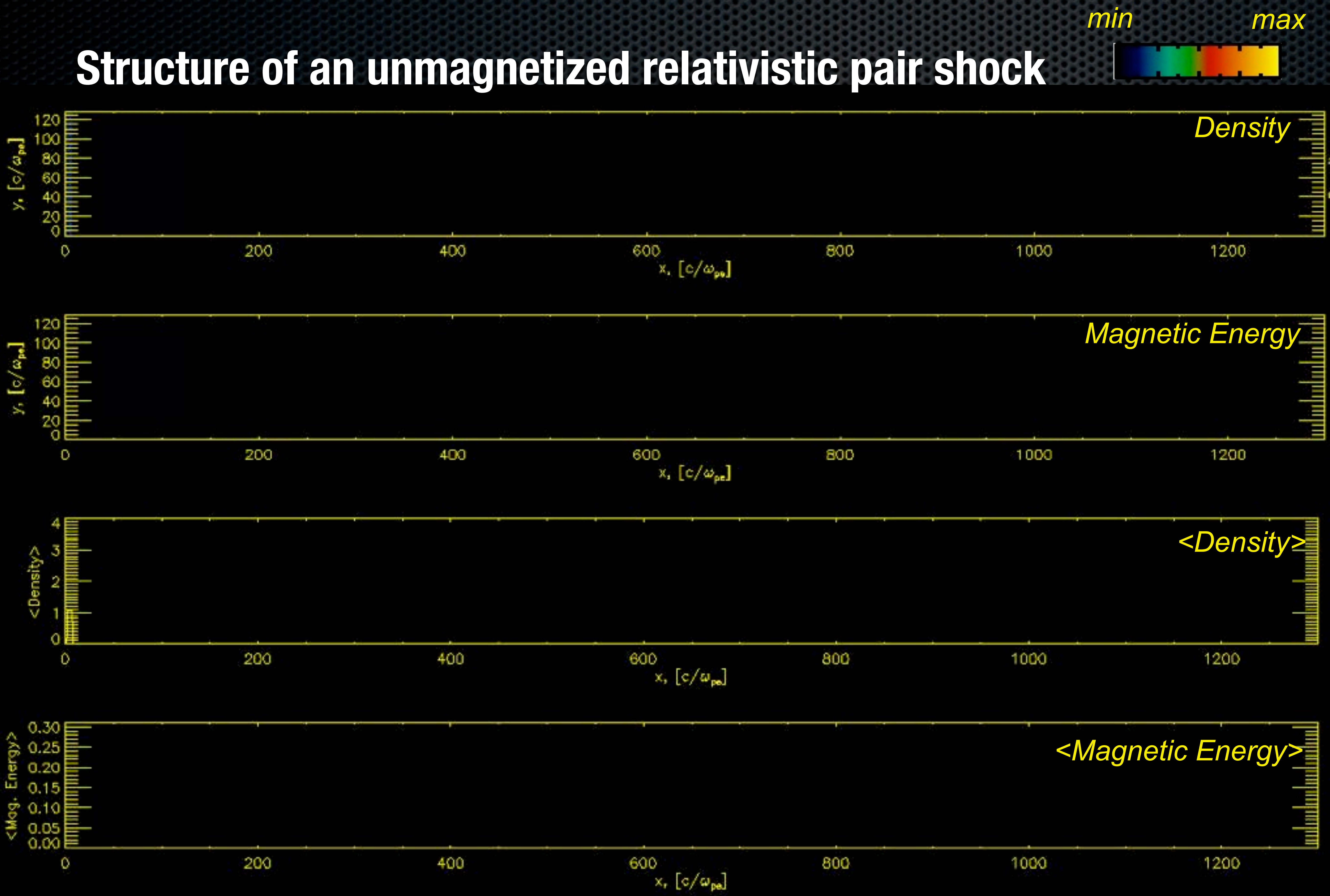


Simulation is in the downstream frame.
We verified that the wall plays no adverse effect by comparing with a two-shell collision.

Largest runs go for ~10000 ω_p^{-1}; sizes up to 200^2x2000 skindepths; 4e10 particles

Collisionless shocks: PIC simulations

Structure of an unmagnetized relativistic pair shock



Collisionless shocks: PIC simulations

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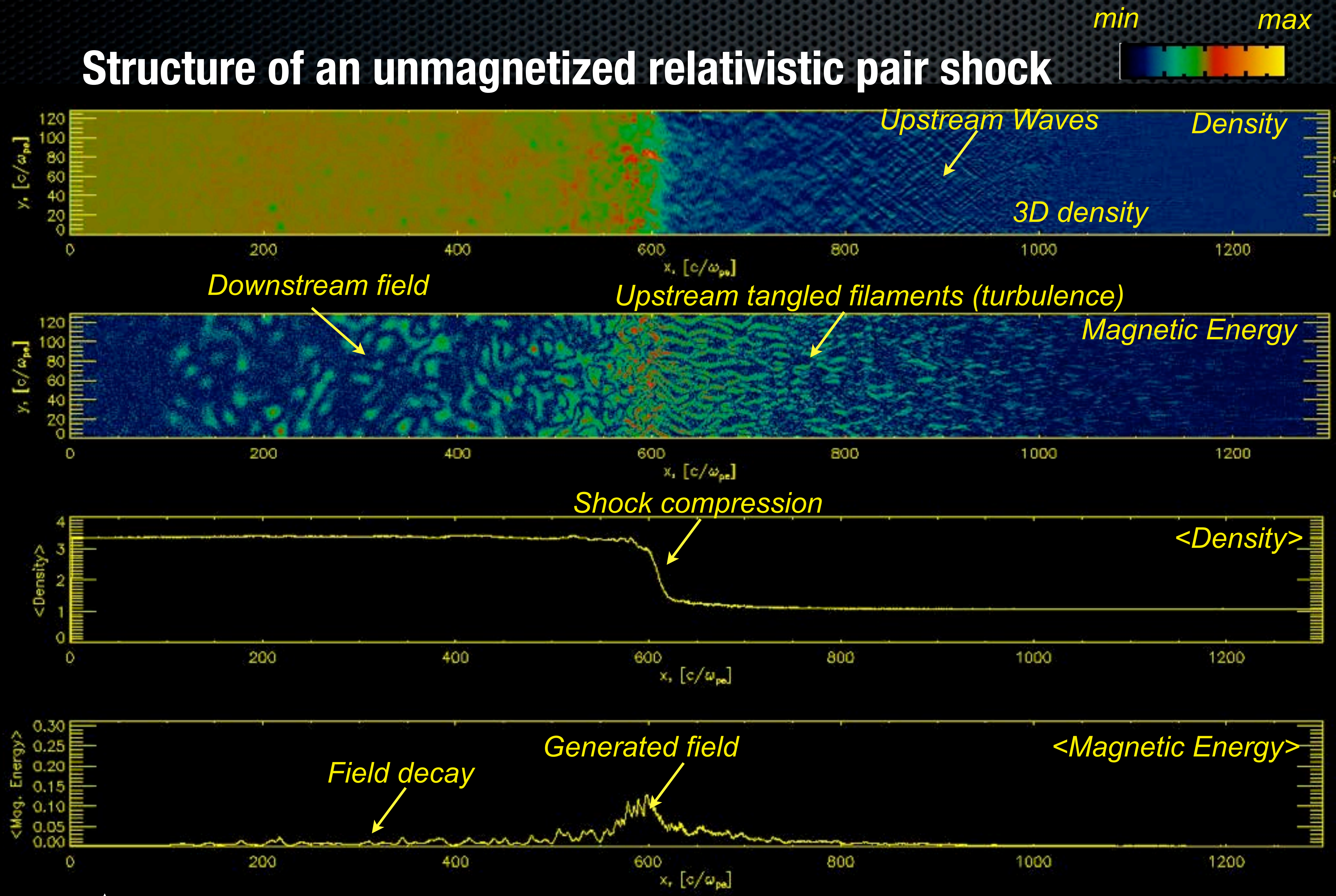
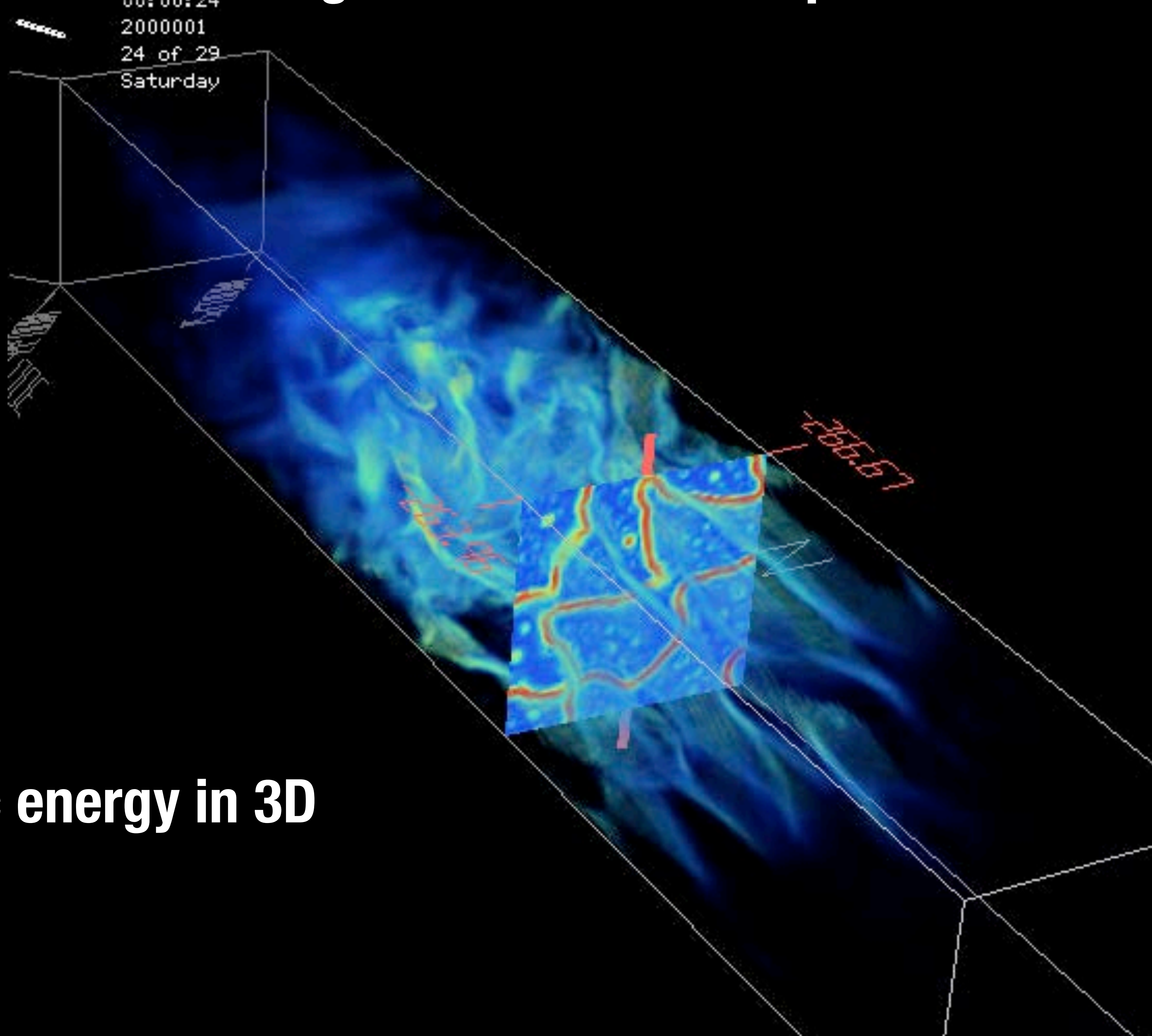


Collisionless shocks: PIC simulations

Structure of an unmagnetized relativistic pair shock:



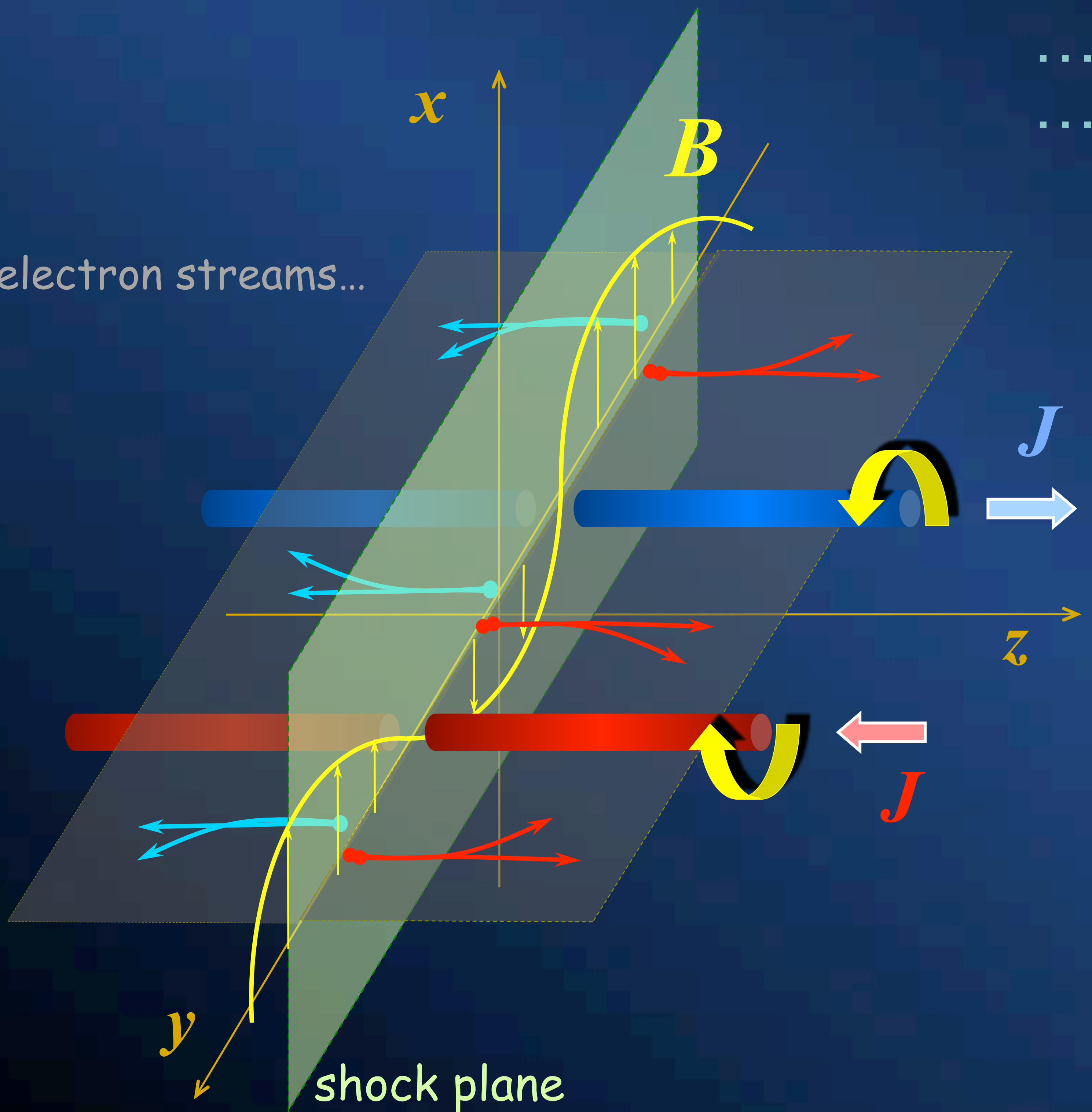
Magnetic energy in 3D

WEIBEL INSTABILITY

(Weibel 1956, Medvedev & Loeb, 1999, ApJ)

… current filamentation …
… *B* – field is generated …

For electron streams…



$$\Gamma^2_{\max} \simeq \frac{\omega_p^2}{\gamma} \qquad k^2_{\max} \simeq \frac{1}{\sqrt{2}} \frac{\omega_p^2}{\gamma_\perp c^2}$$

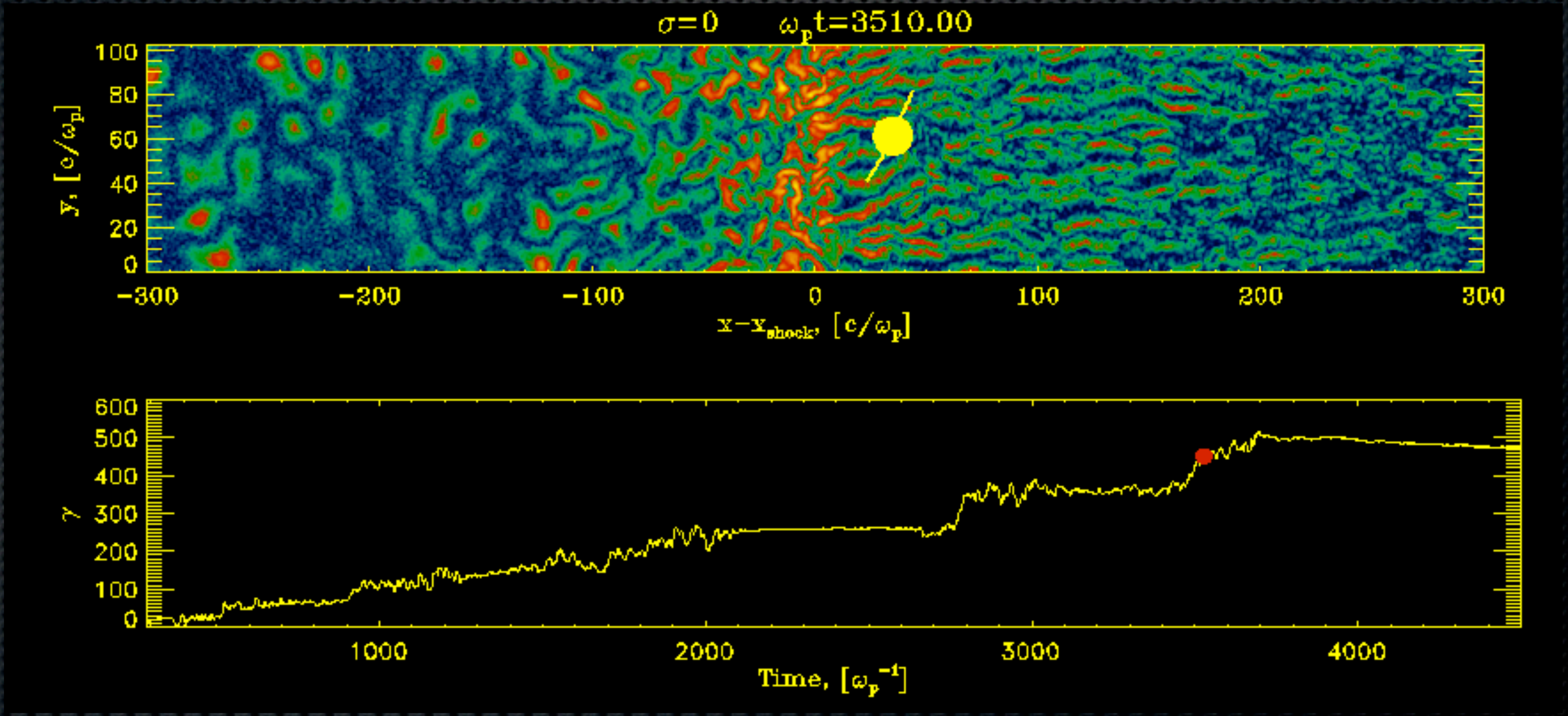
slide courtesy of M. Medvedev

Particle acceleration

Self-generated magnetic turbulence scatters particles across the shock; each crossing results in energy gain -- Fermi process

Magnetic filaments

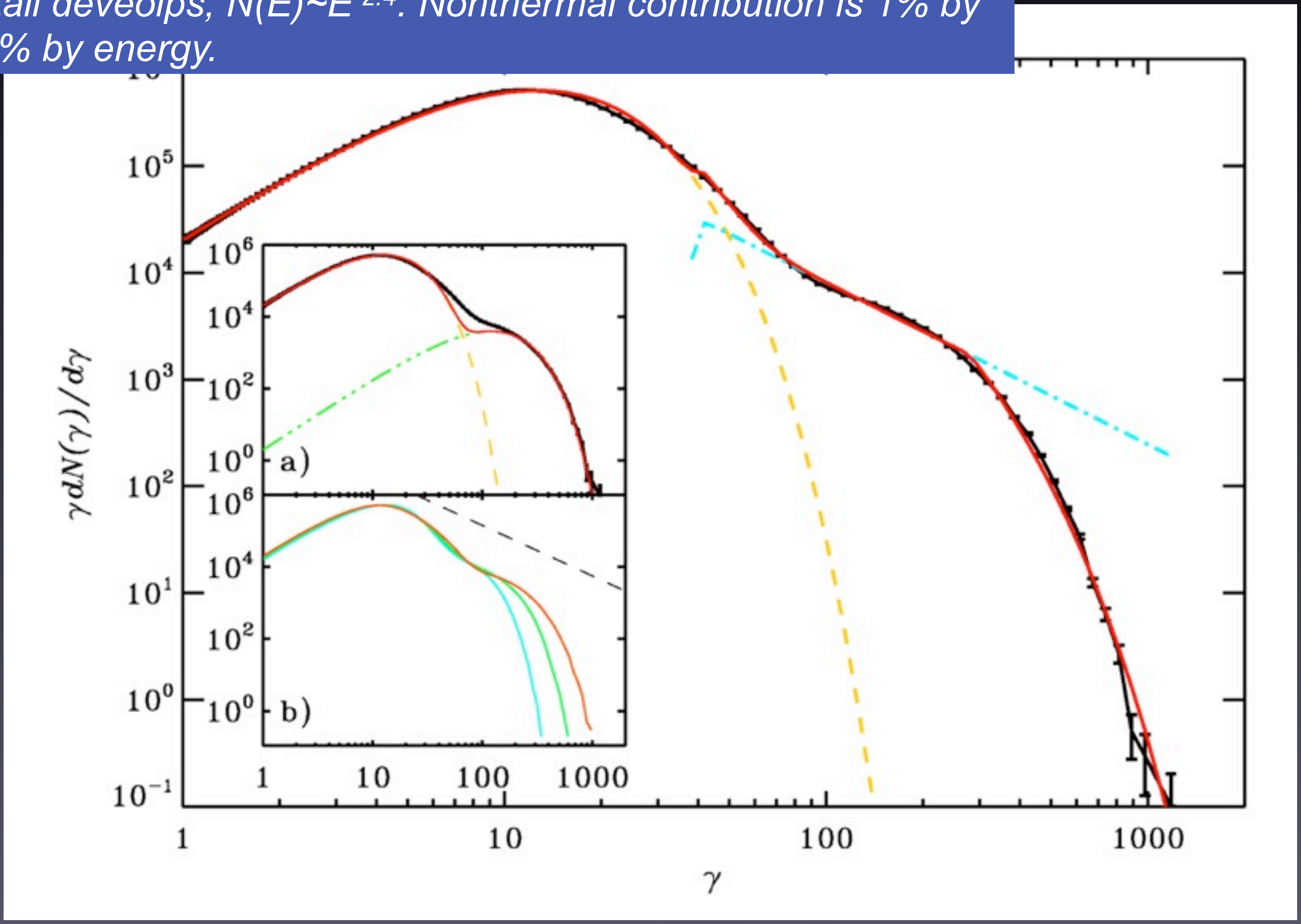
Particle energy



Unmagnetized Weibel-mediated pair shock:

downstream spectrum: development of nonthermal tail

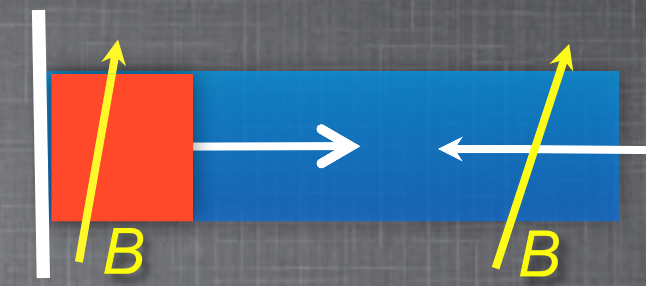
Nonthermal tail deveolps, $N(E)\sim E^{-2.4}$. Nonthermal contribution is 1% by number, ~10% by energy.

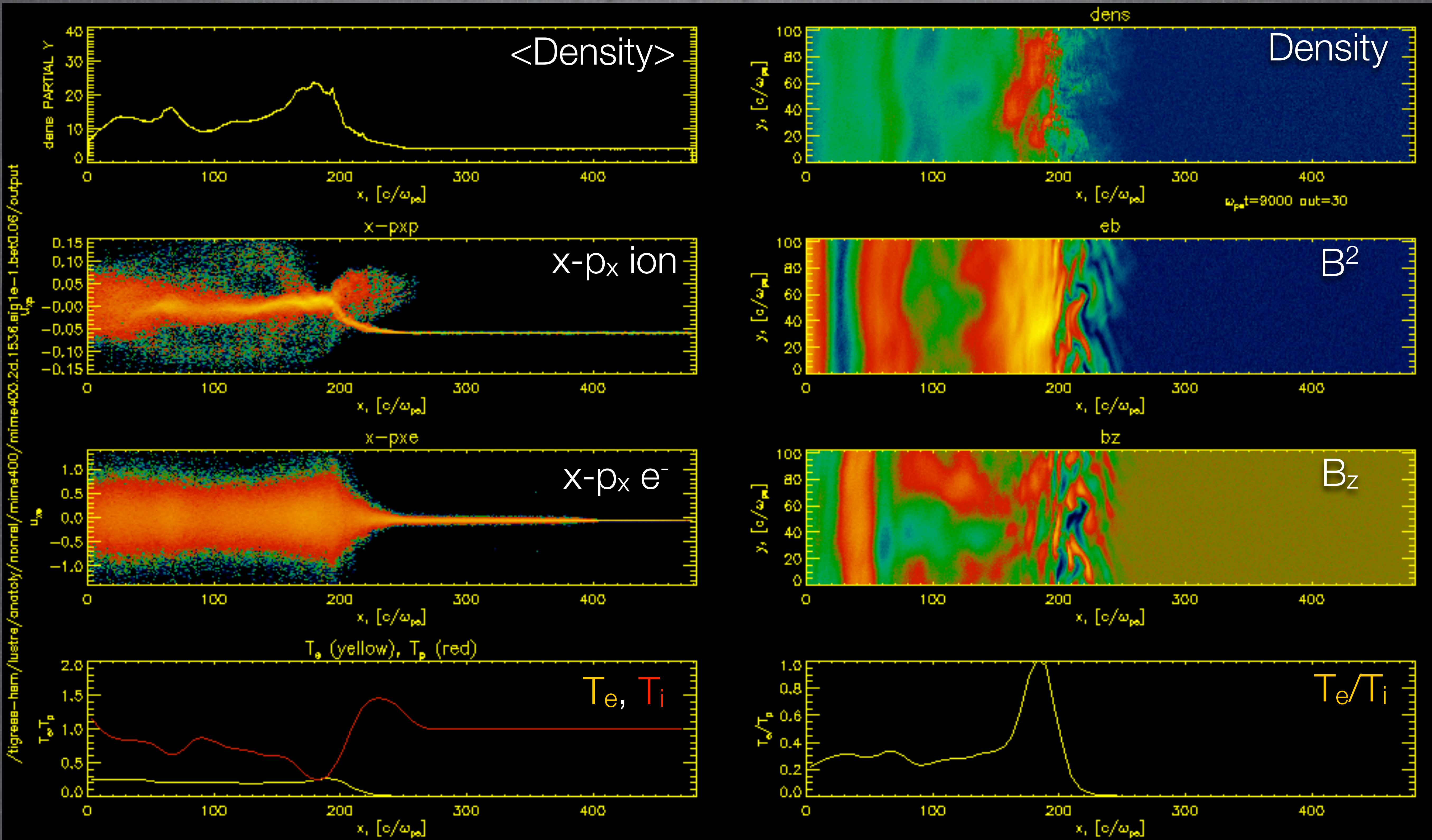


A.S. 2008, ApJ, 682, L5

Structure of magnetized shocks

mi/me=400, v=18,000km/s, Ma=5, quasi-perp 75° inclination

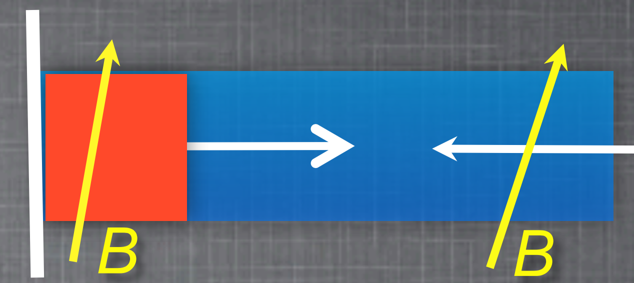


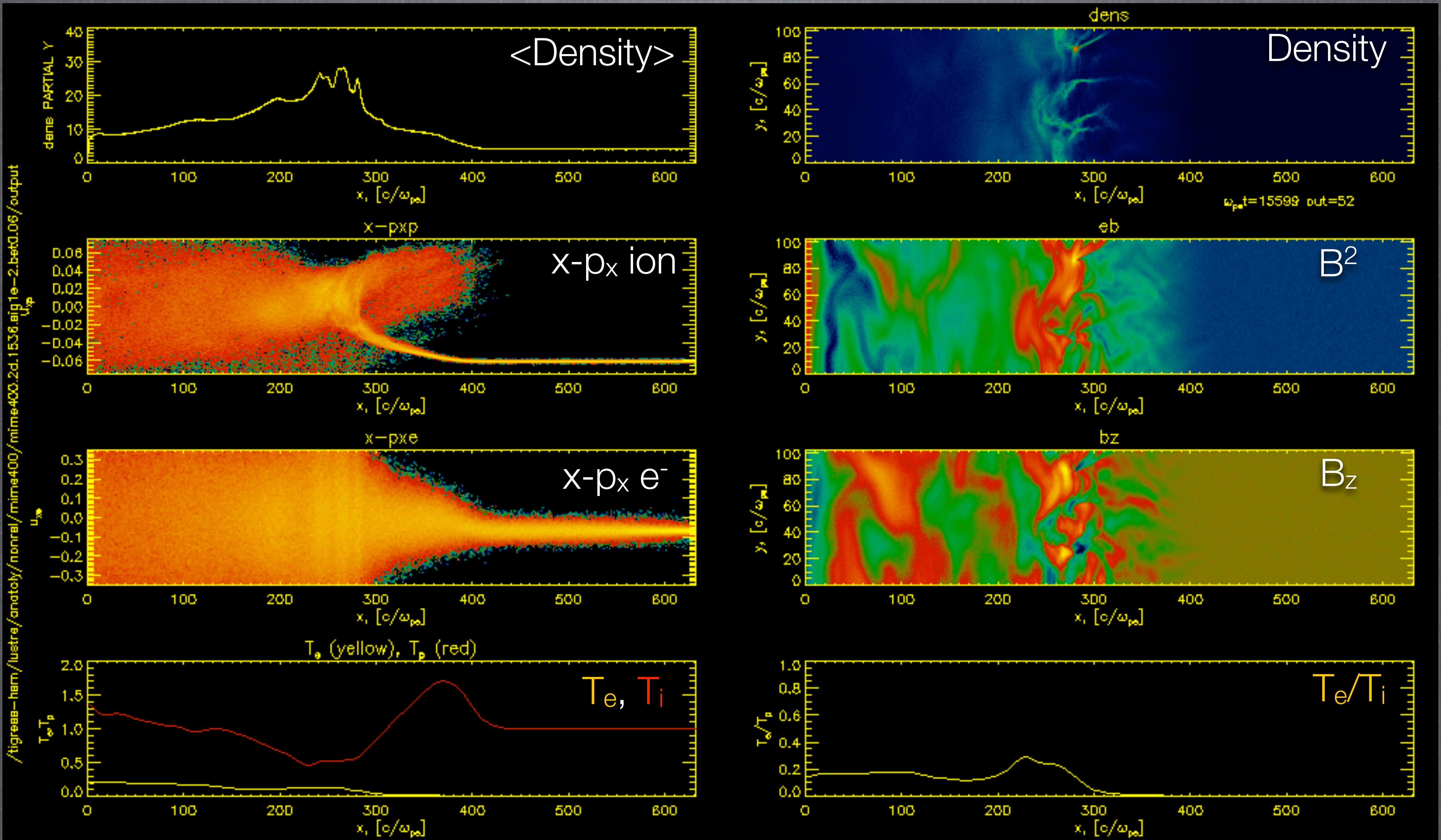


Shock foot, ramp, overshoot, returning ions, electron heating, whistler(?) waves.

Structure of magnetized shocks

mi/me=400, v=18,000km/s, Ma=15 quasi-perp 75° inclination

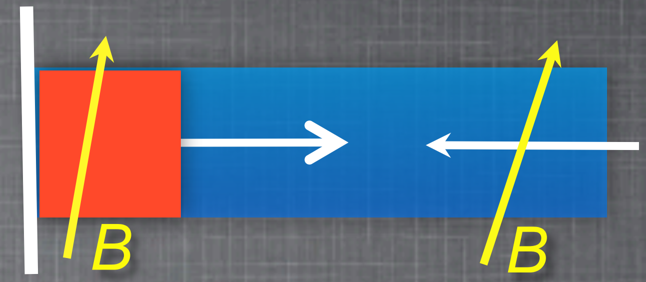


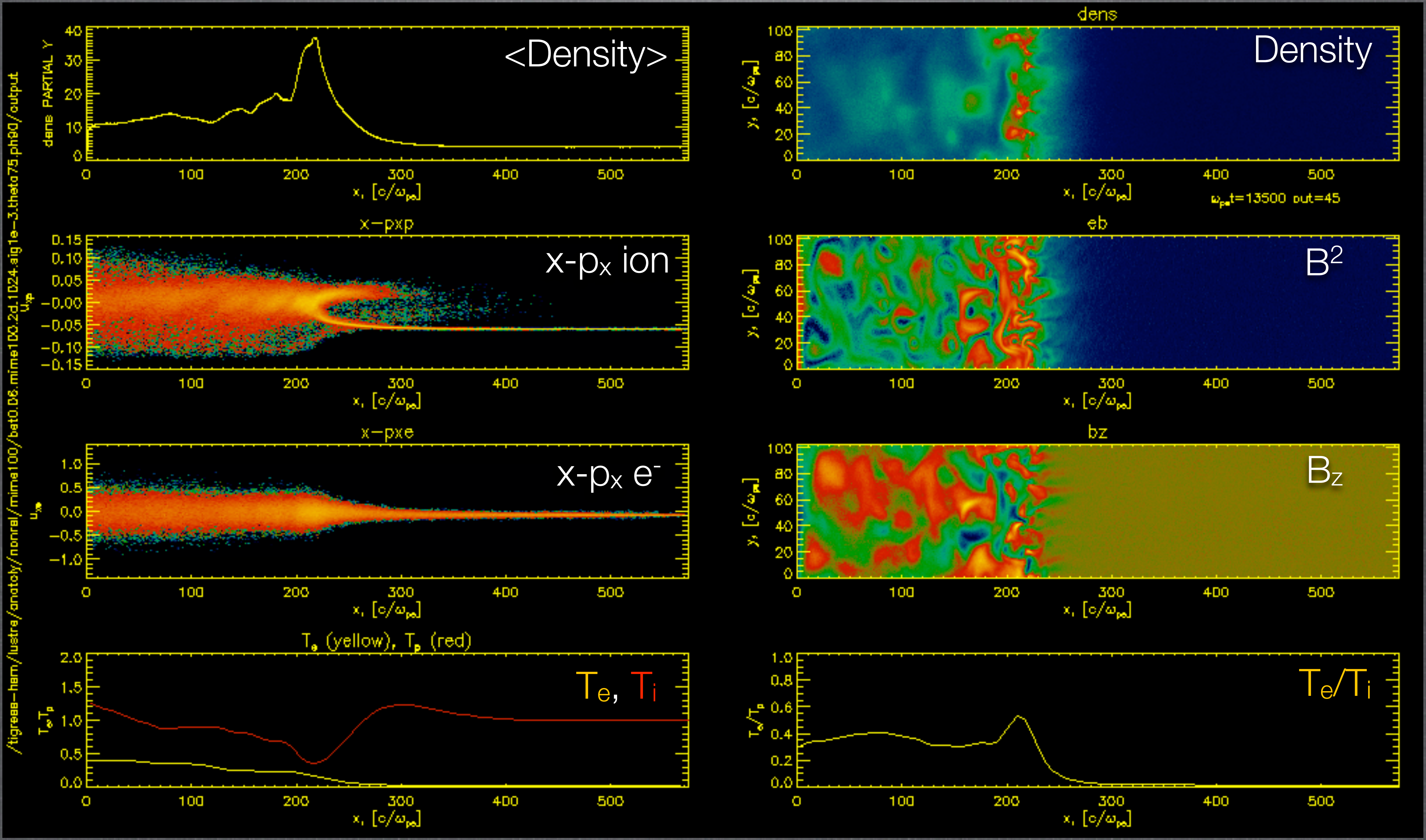


Shock foot, ramp, overshoot, returning ions, electron heating, whistler(?) waves, spectra.

Structure of magnetized shocks

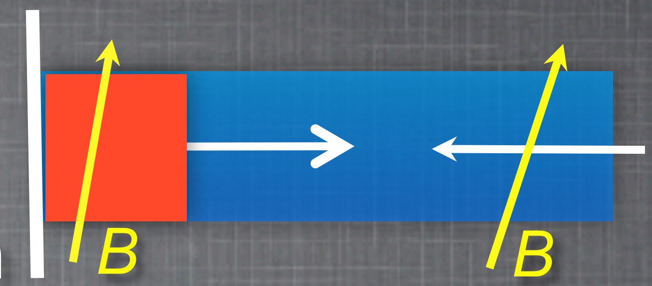
mi/me=100, v=18,000km/s, Ma=45 quasi-perp 75° inclination

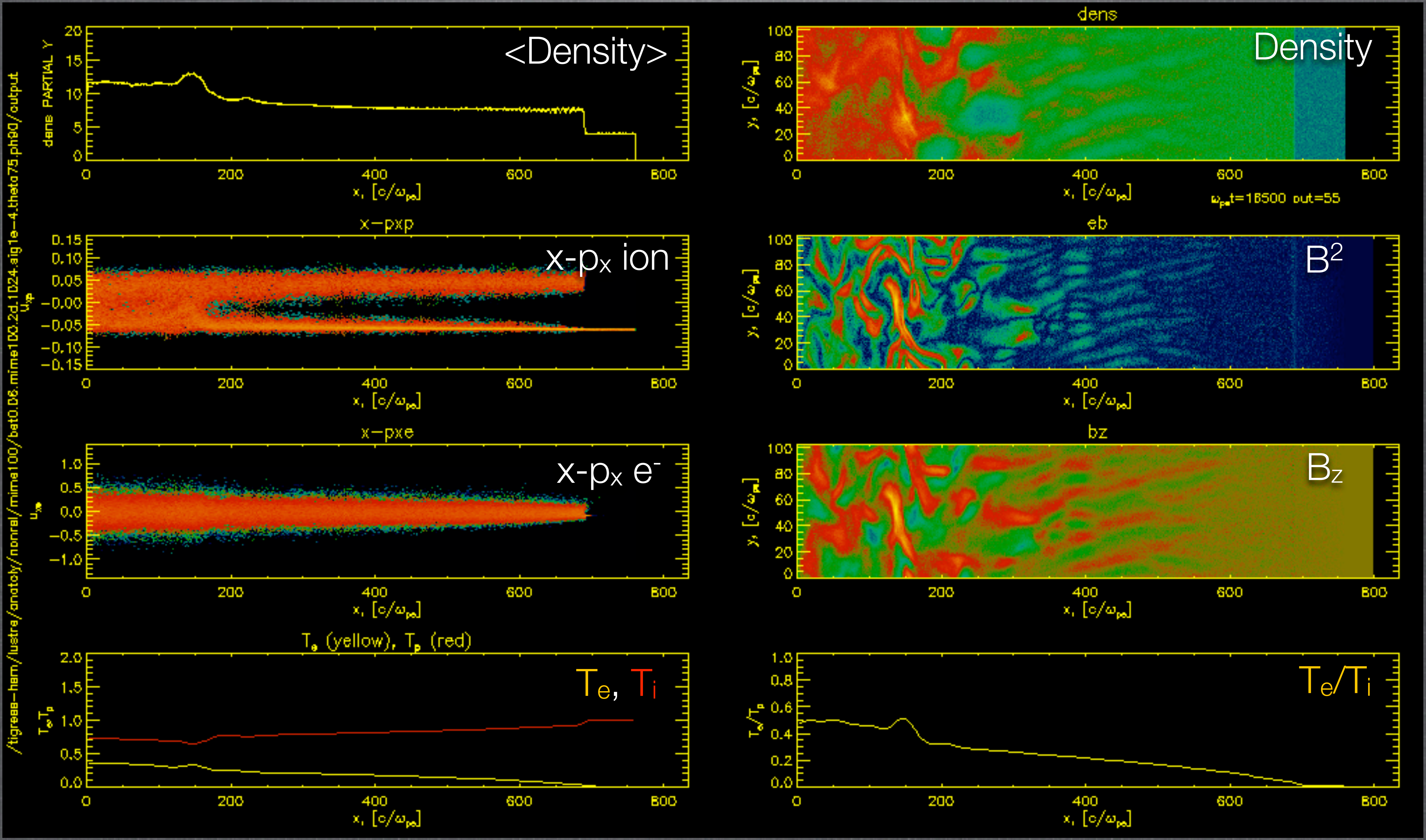




Structure of magnetized shocks

mi/me=100, v=18,000km/s, Ma=140 quasi-perp 75° inclination

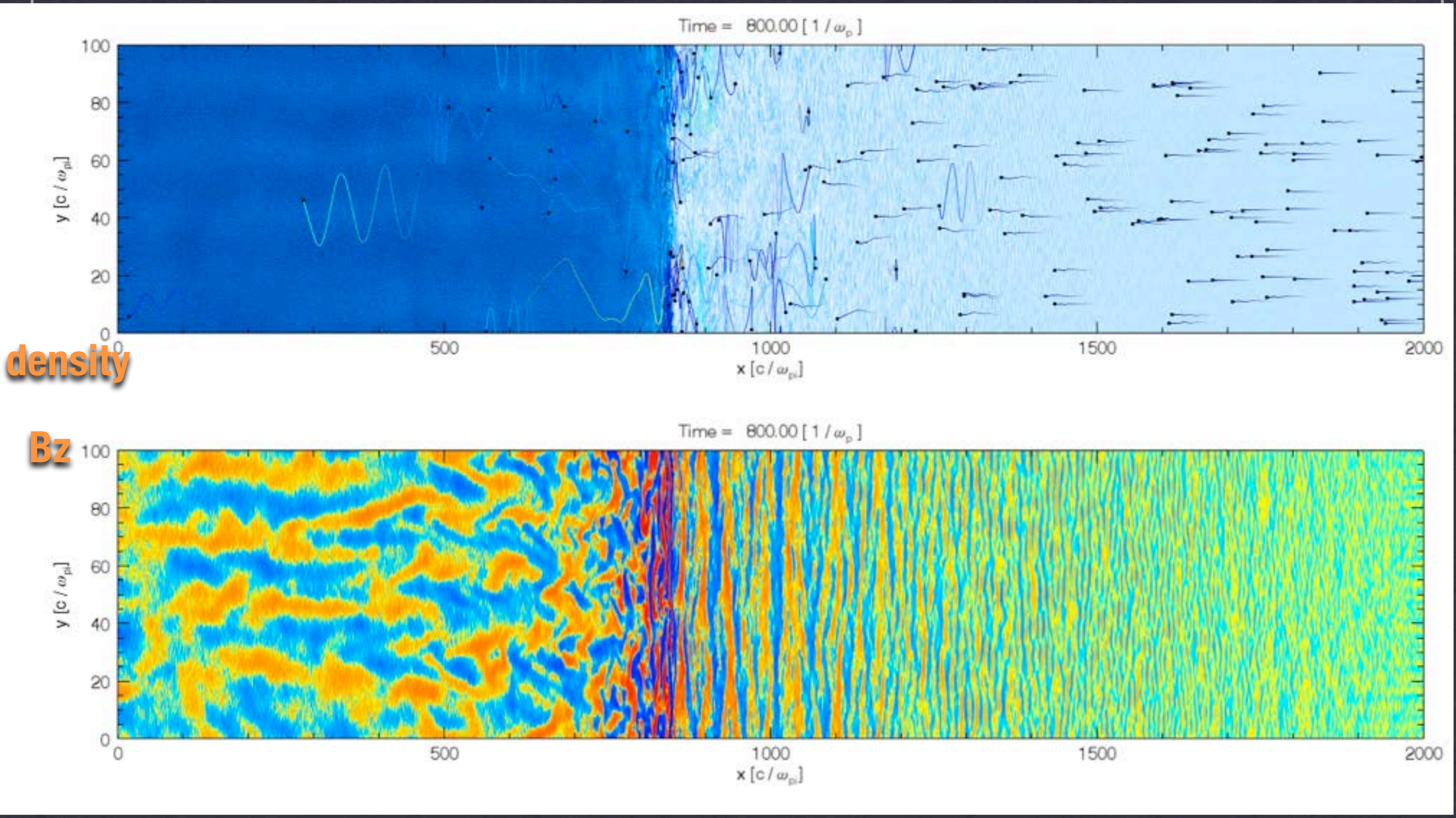




Return to filamentation as B field decreases

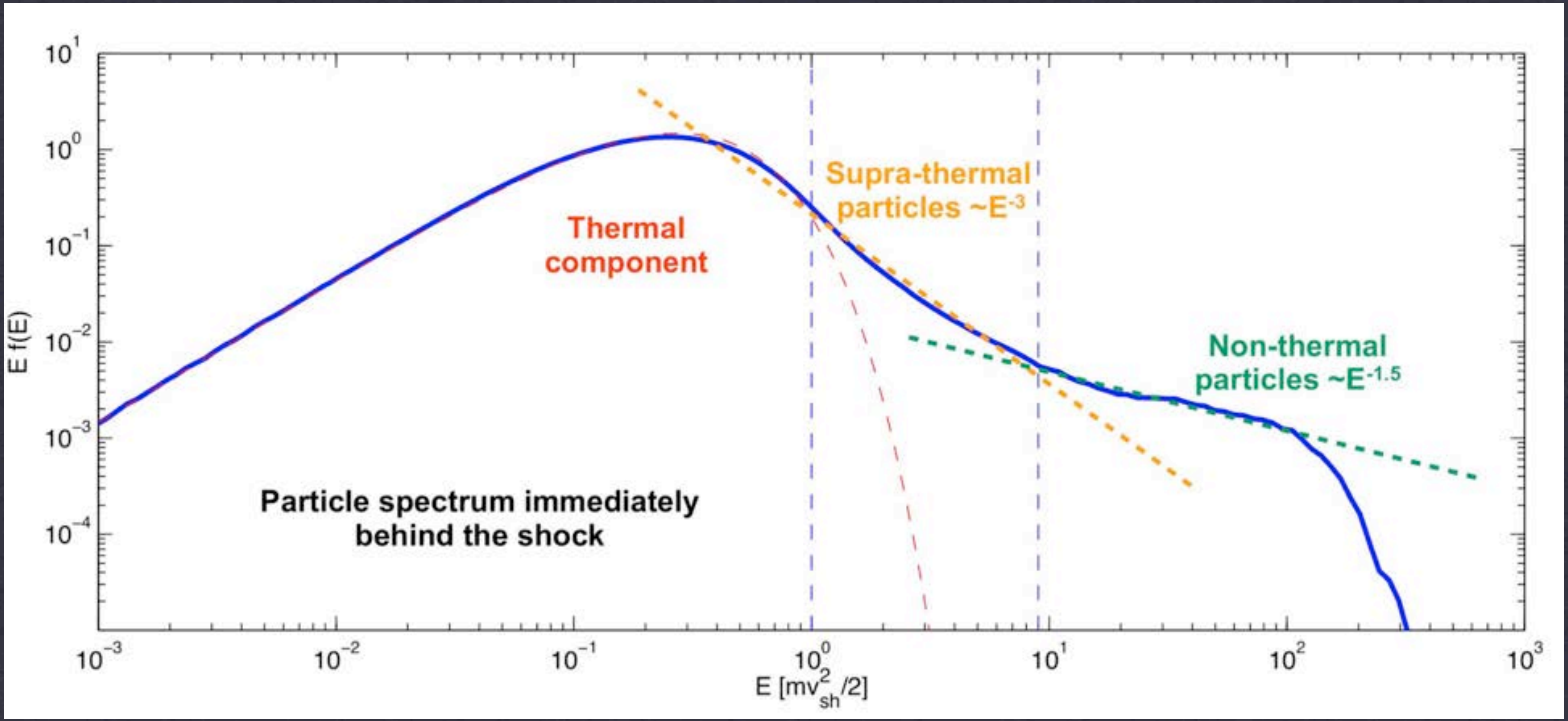
Quasi-parallel magnetized shocks

Ma=3.1, parallel



Ion spectrum

1% by number and ~10% by energy of the flow are in the nonthermal tail



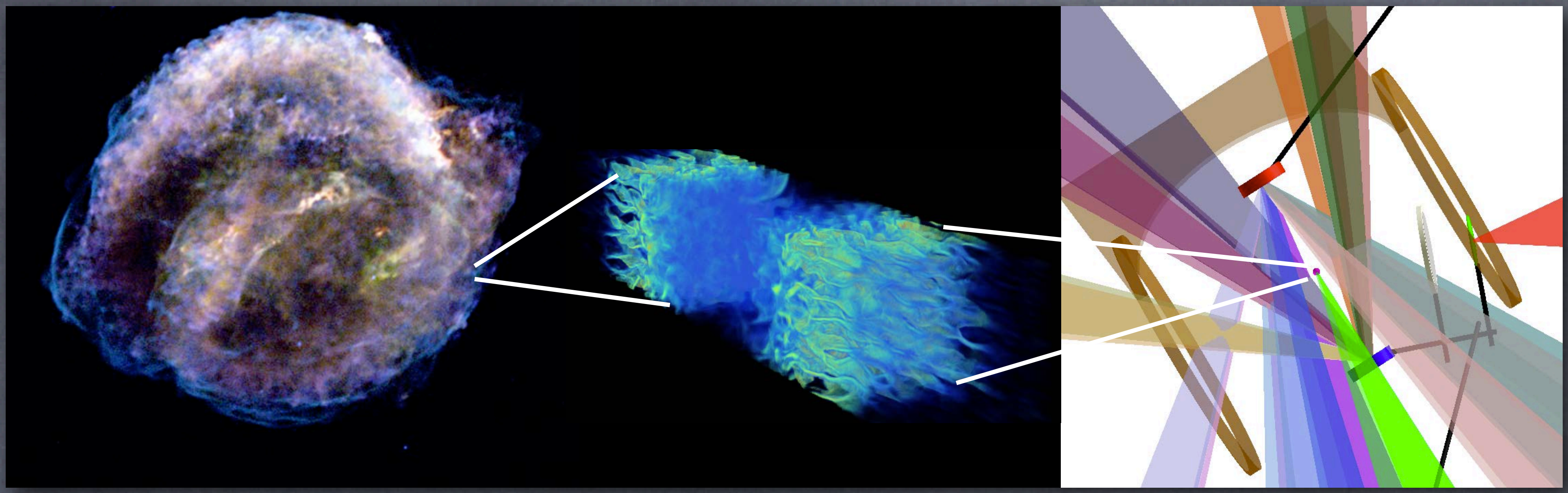
(Gargate+AS 2012, Caprioli+AS 2013)

Collisionless shocks: simulations

- Simulation predict distinct regimes of shock formation: unmagnetized (Weibel) vs magnetized shocks
- Acceleration efficiency is set by physics of the shock transition (first passing through the shock)
- Acceleration depends on field strength and orientation

Can we test these predictions in controlled laboratory experiments?

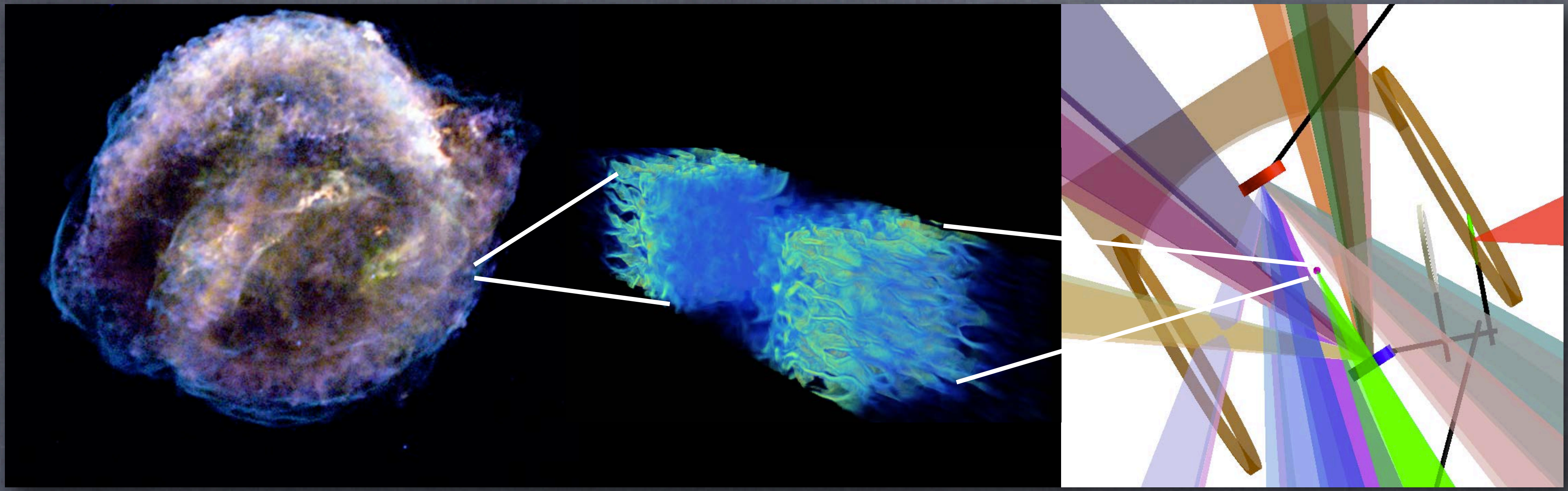
What do we want to learn about shocks from experiments?



Universe ⟺ microphysics ⟺ experiments

- Test shock mediation regimes: unmagnetized vs magnetized
- Mechanisms of particle injection at shocks
- Efficiency of electron heating and energy exchange at shocks
- Mechanisms of magnetic field amplification and turbulence excitation

What do we need experiments to satisfy?



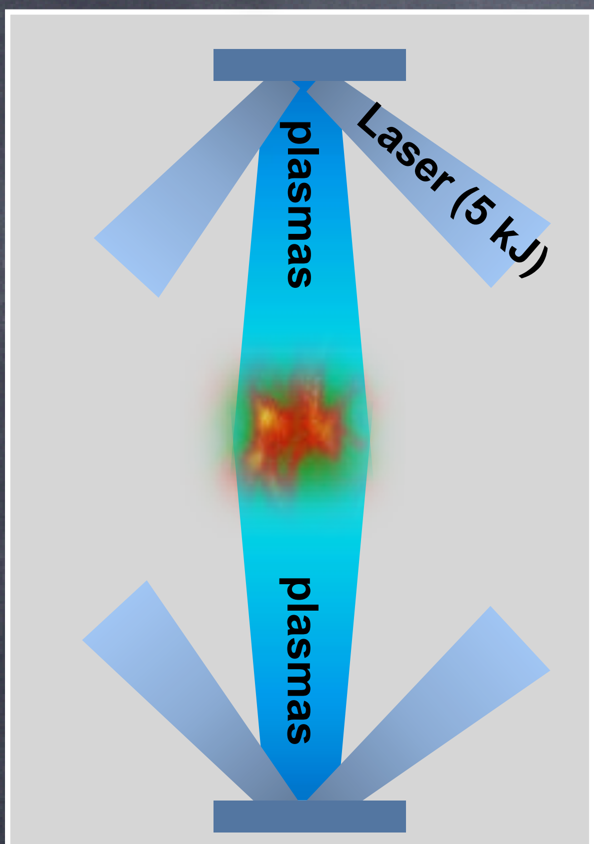
Universe ⟺ microphysics ⟺ experiments

- Collisionless conditions (requires high velocities)
- Sufficient longitudinal and transverse size to form shocks
- Ability to dial magnetization and field geometry
- Availability of particle and field diagnostics

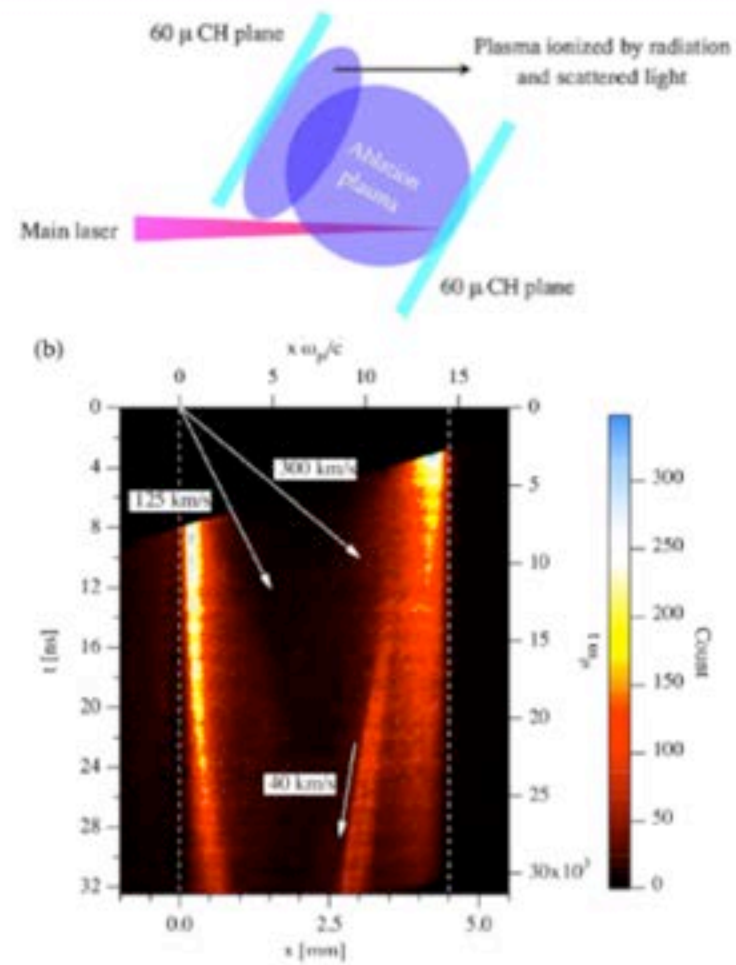
Dimensionless astro parameters can be reproduced in the lab

Colliding beam experiments

Omega setup

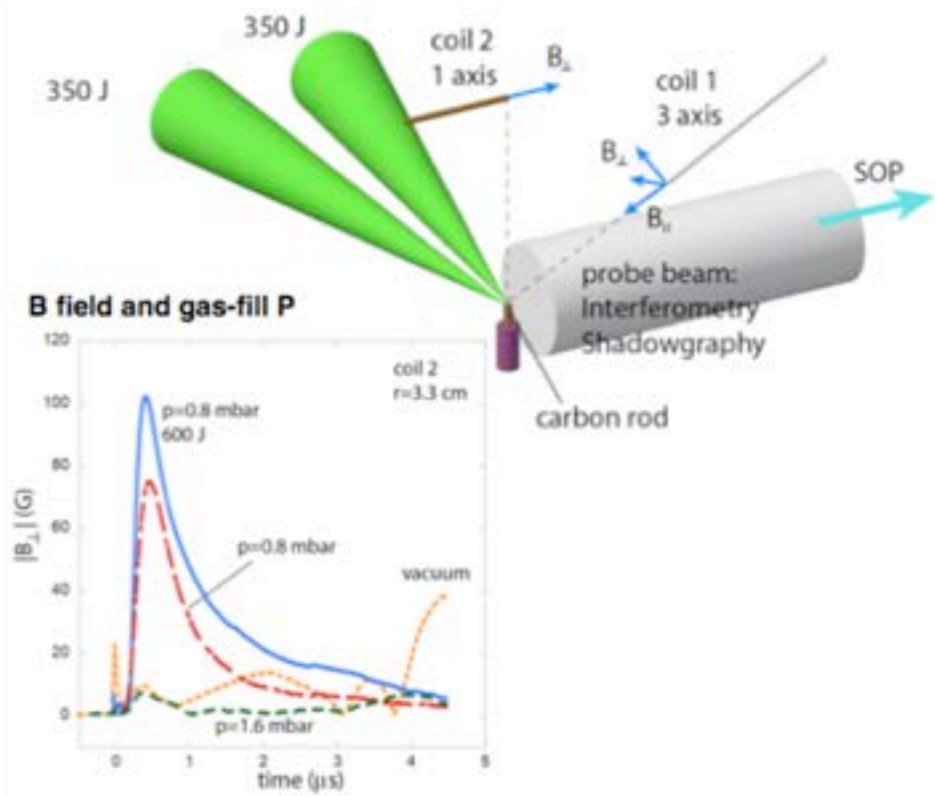


Gekko experiment (Sakawa team)



Shock formation from electrostatic plasma instability
[Kuramitsu et al, PRL (2011)]

LULI experiment (Gregori team)



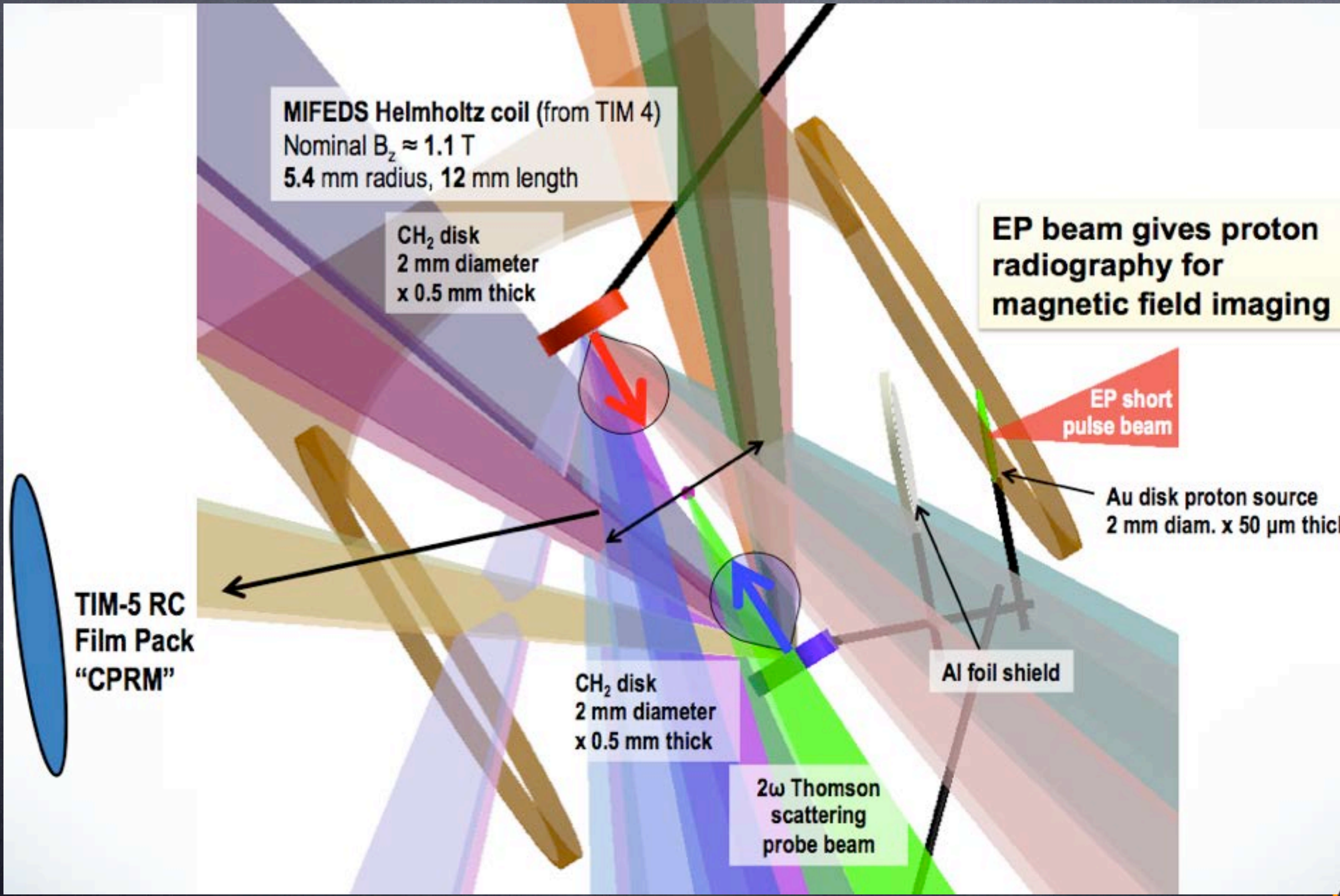
- **Target chamber filled with helium or nitrogen gas (p~0.1-10 mbar)**
- **Bdot probe measured magnetic field**

Possible magnetic field from Biermann battery effect
[Gregori, (2012)]

Colliding beams have been used on several medium-scale laser experiments to study shock formation

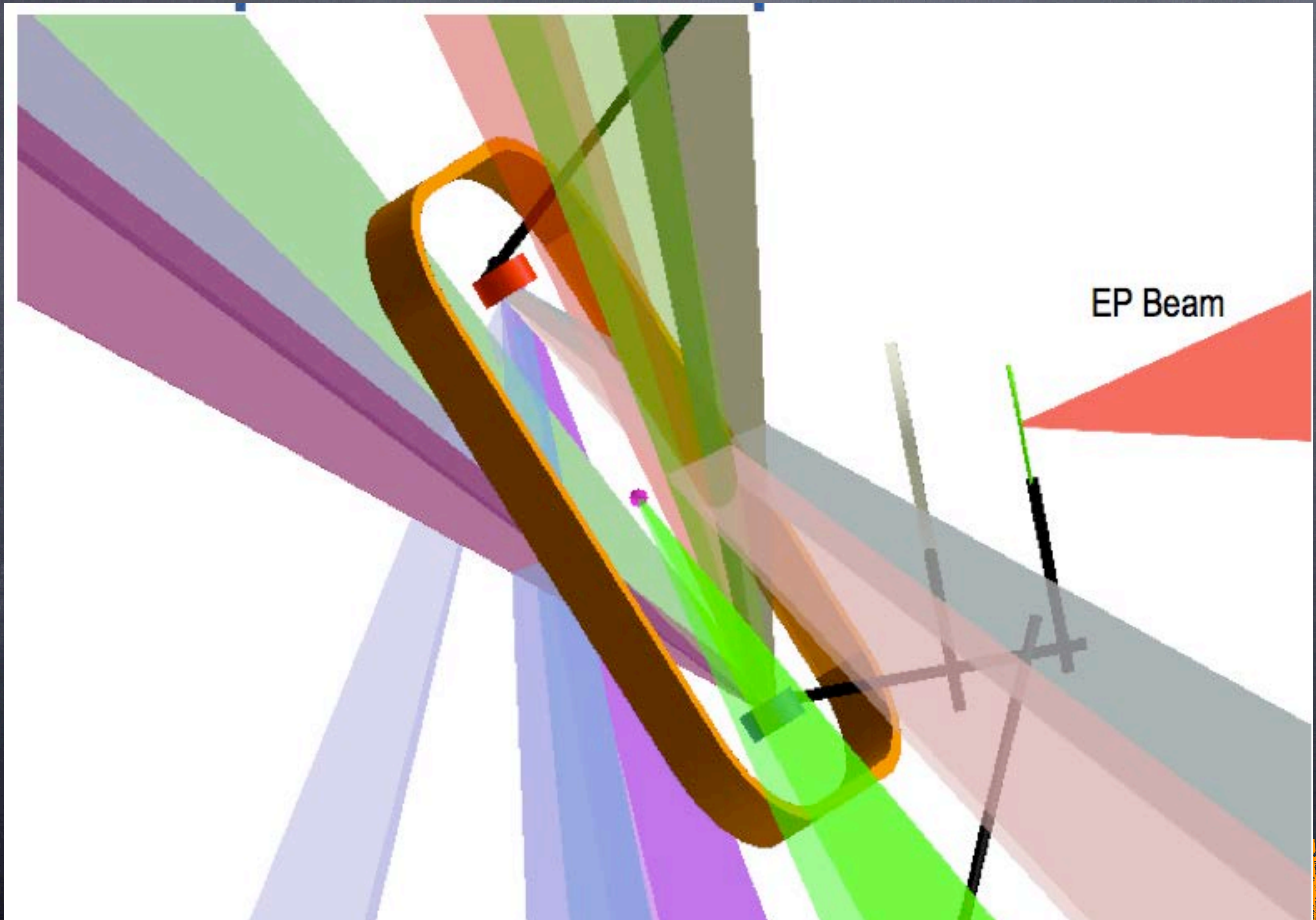
Colliding beam experiments on Omega Laser

ACSEL collaboration (Astrophysical Collisionless Shock Experiments with Lasers)



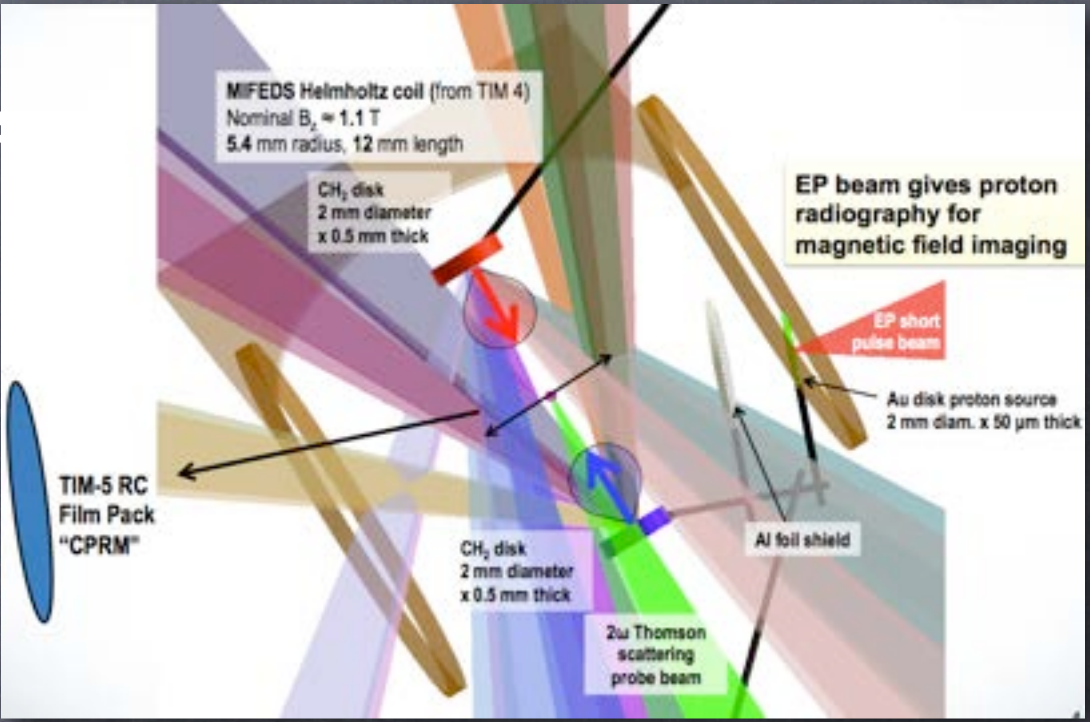
Colliding beam experiments on Omega Laser

ACSEL collaboration (Astrophysical Collisionless Shock Experiments with Lasers)



Colliding beam experiments on Omega Laser

- Expected conditions: 10^{15} W/cm^2, 1ns pulse
- 1000-2000 km/s ablation flow of CH_2 & Be
- 10^{18}-10^{19} cc plasma densities
- Target separation 8 mm; mfp > 4 cm
- External field: 1-8 T (depending on config)
- Interaction region parameters:



$$\sigma \equiv \frac{B^2/4\pi}{n m_i v^2/2} = \frac{2}{M_A^2} = \left(\frac{\omega_{ci}}{\omega_{pi}}\right)^2 \left(\frac{c}{v}\right)^2 = \left[\frac{c/\omega_{pi}}{R_{Li}}\right]^2$$

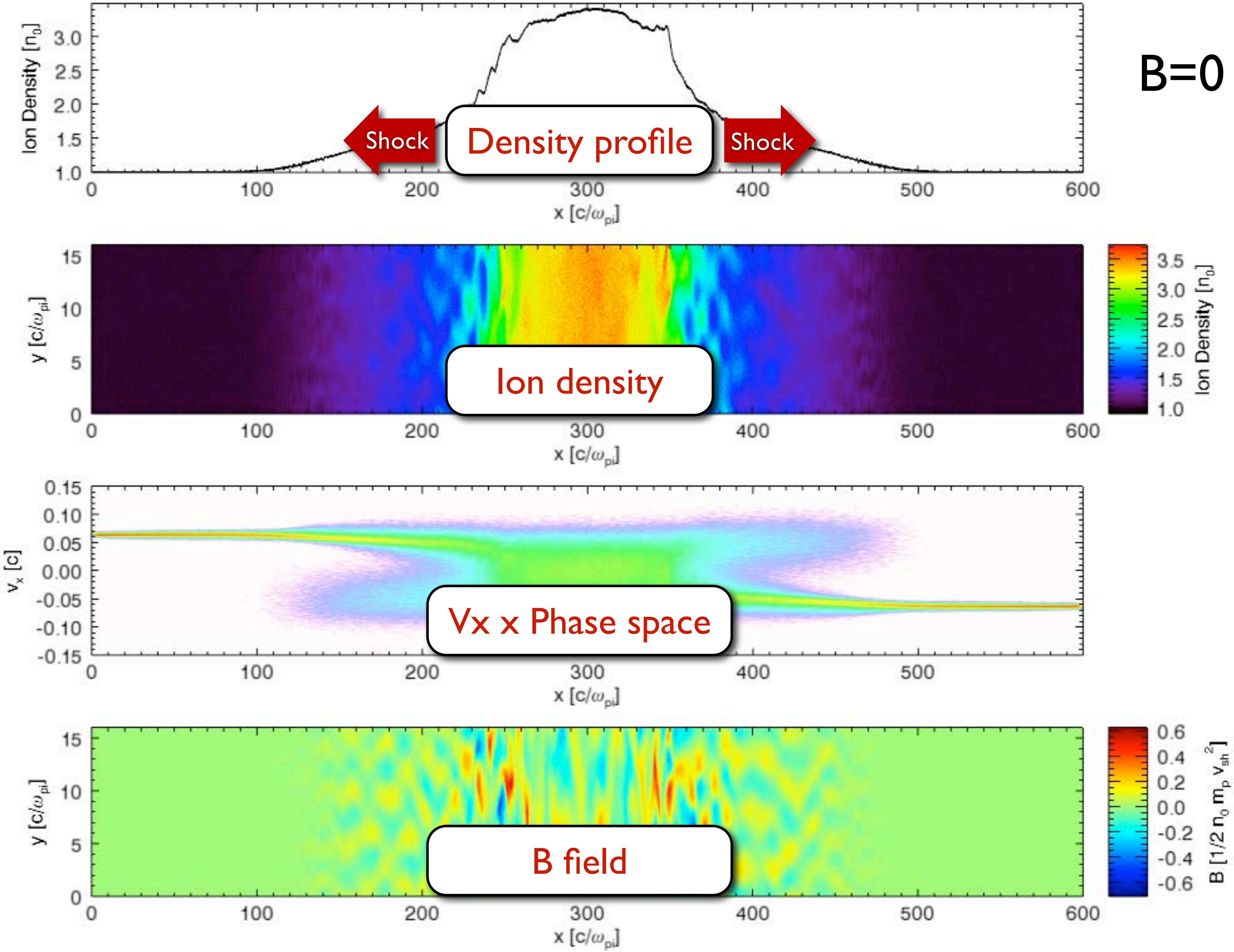
$$\sigma = 10^{-3}\left(\frac{B}{1T}\right)^2 \left(\frac{10^{18}\mathrm{cm}^{-3}}{n}\right)\left(\frac{1000\mathrm{km/s}}{v}\right)^2\left(\frac{m_p}{m_i}\right)$$

$$c/\omega_{pi} = c/[4\pi n Z^2 e^2/A m_p]^{1/2} = 250\mu\mathrm{m}\sqrt{A}/Z(10^{18}\mathrm{cm}^{-3}/n)^{1/2}$$

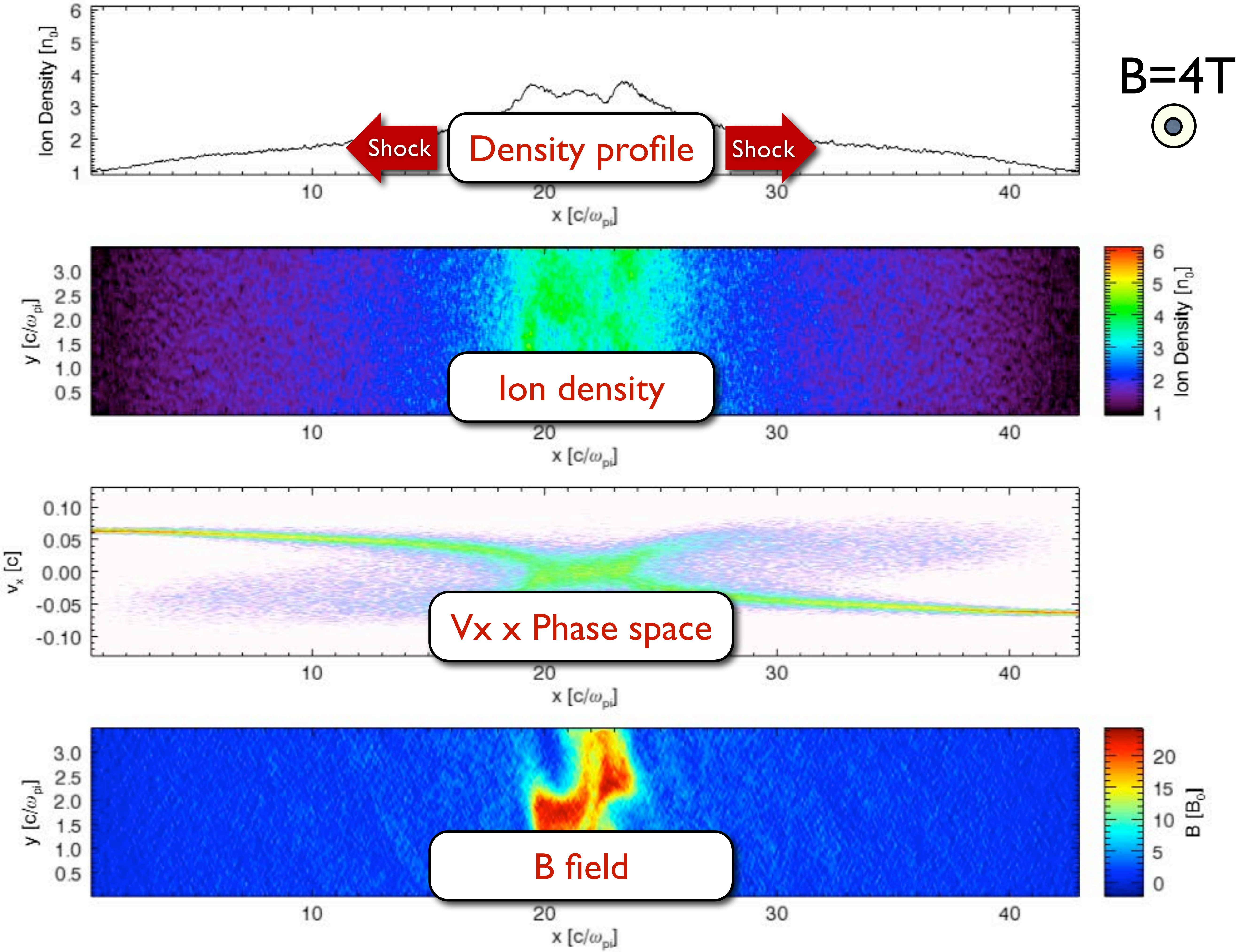
$$R_{Li} = 1\mathrm{cm}\left(\frac{A}{Z}\right)\left(\frac{v}{1000\mathrm{km/s}}\right)\left(\frac{1T}{B}\right)$$

We modeled the experiment with particle-in-cell simulations

Sonic Mach~10-20, Alfenic M~30-100

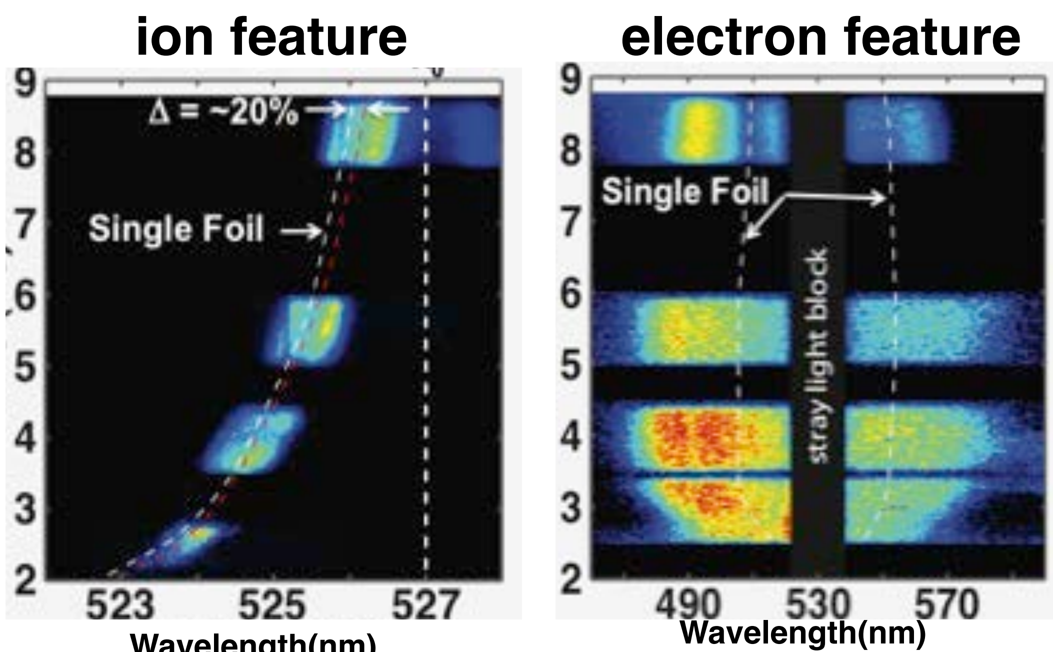


B=0
Density profile
Shock
Shock
Ion density
Vx x Phase space
B field
Ion Density [n0]
x [c/ωpi]
y [c/ωpi]
vx [c]
B [1/2 n0 mp vsh2]

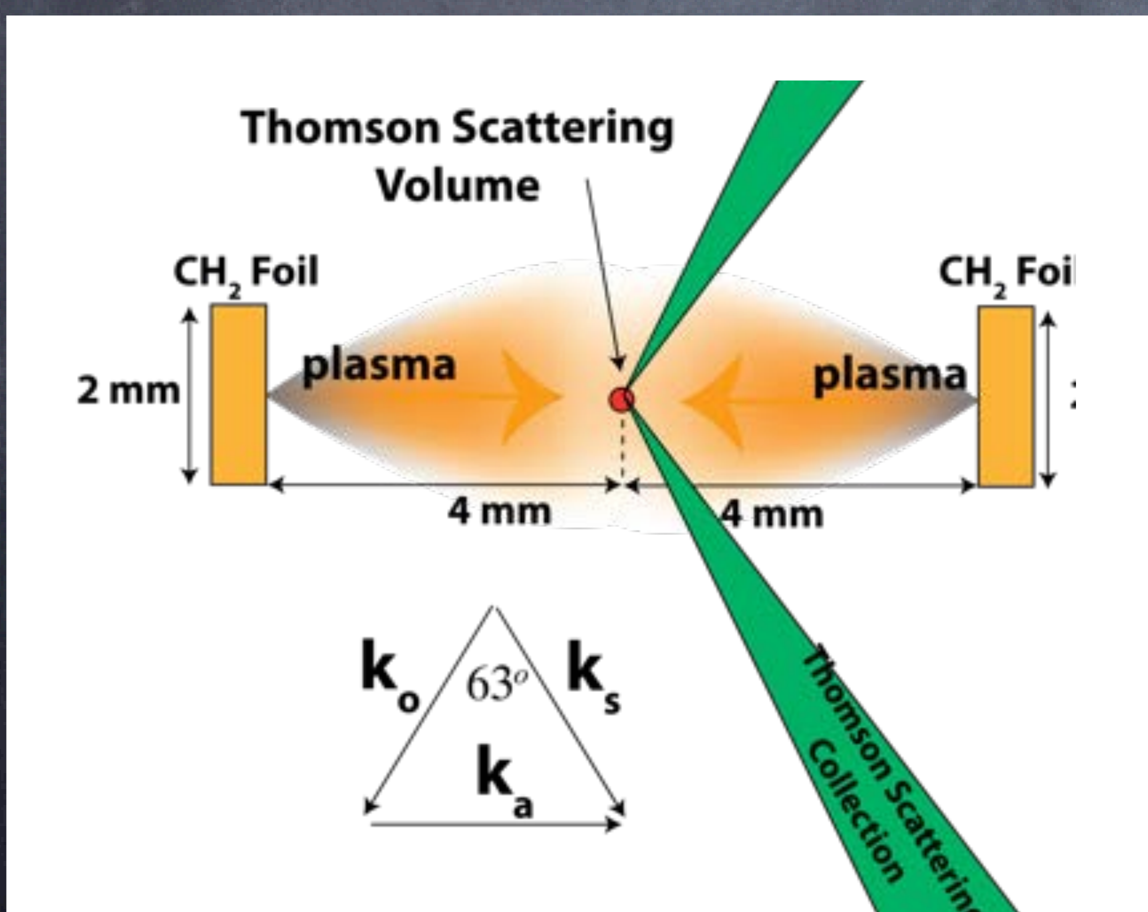

B=4T
Density profile
Shock
Shock
Ion Density [n_0]
x [c/ω_{pi}]
Ion density
y [c/ω_{pi}]
Vx x Phase space
v_x [c]
B field
B [B_0]

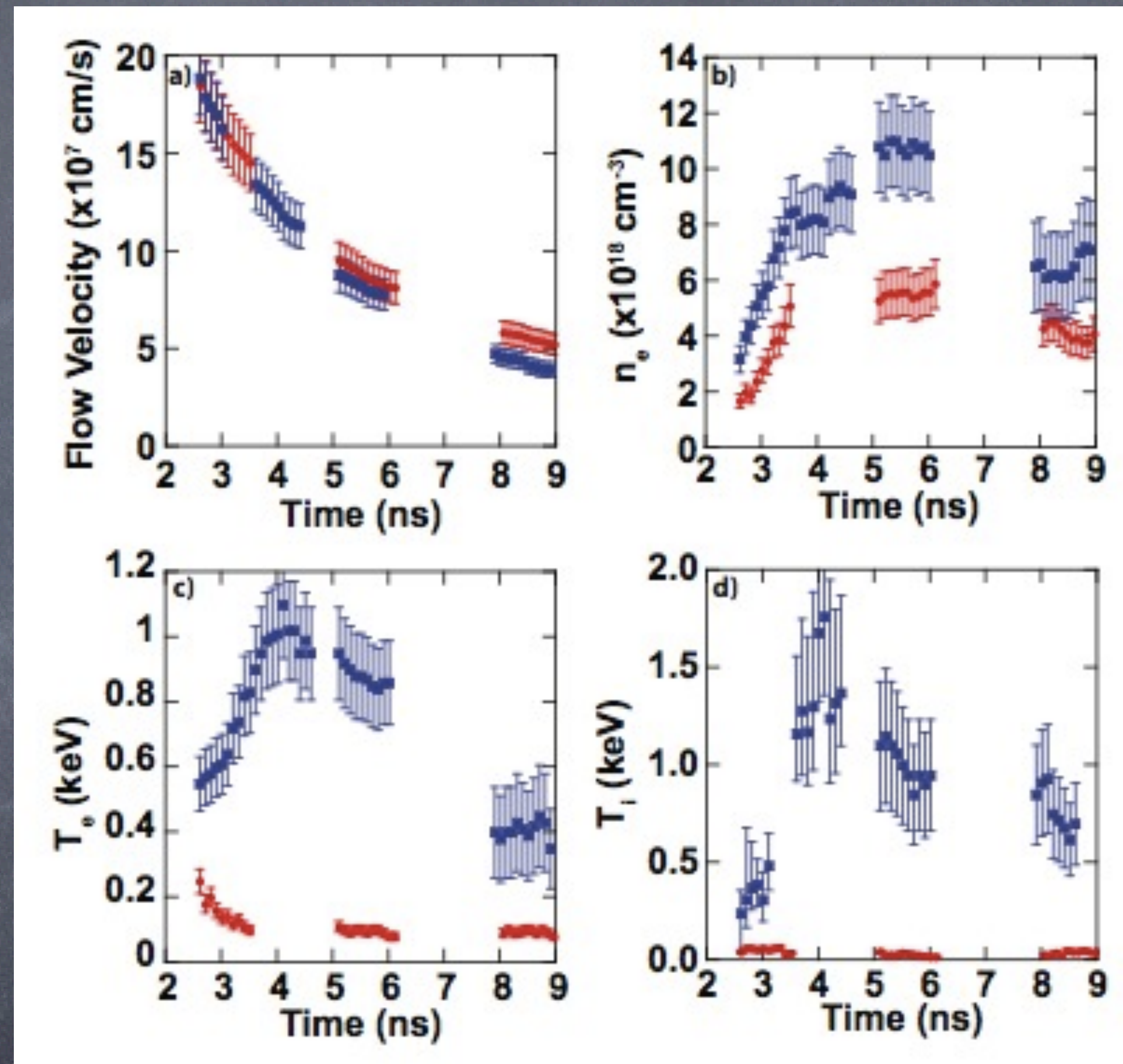
Diagnostics i): Thomson scattering

Thomson scattering is giving plasma conditions



Ross et al (2012)



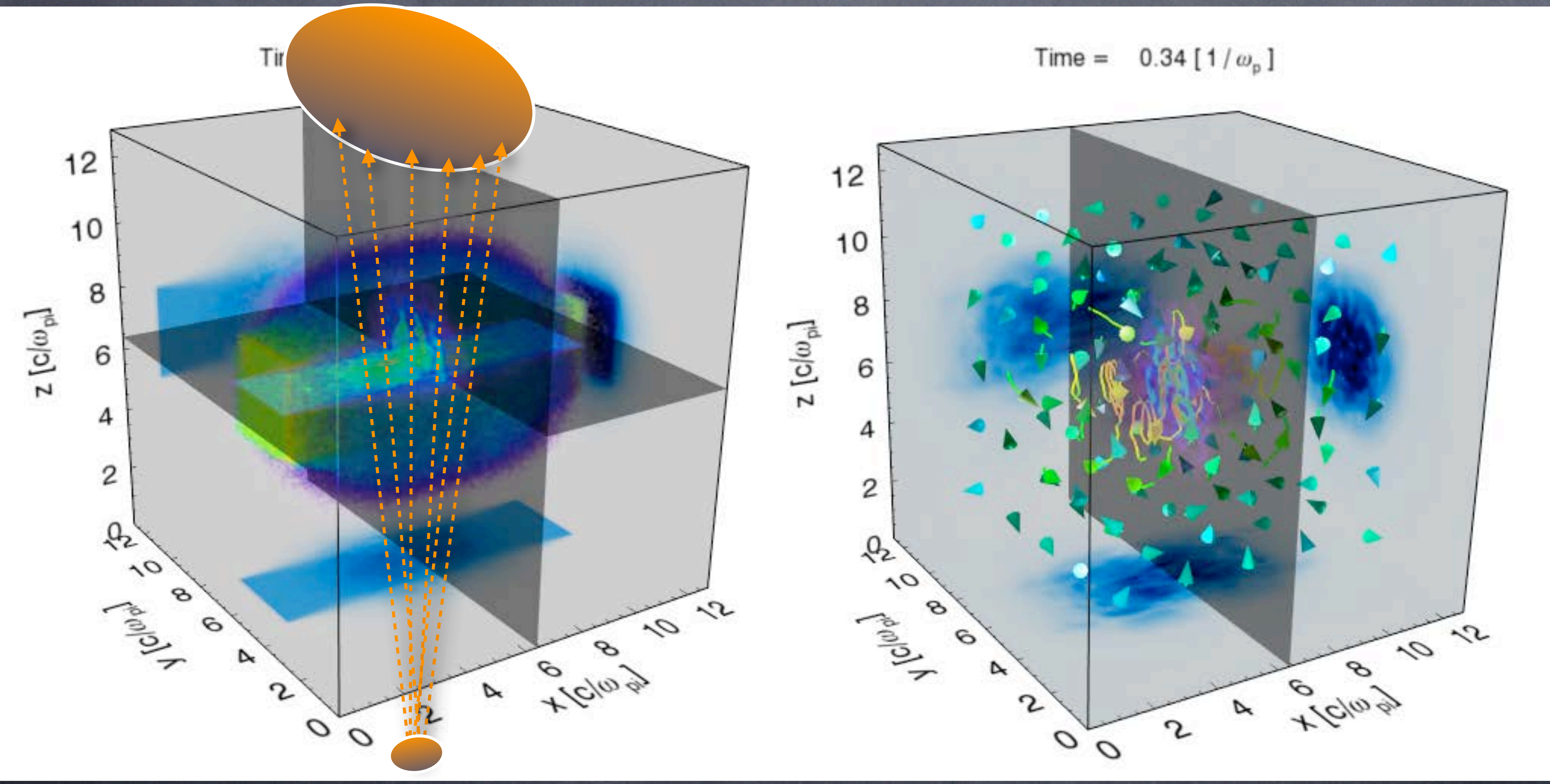


Single (red) vs double (blue) foil run

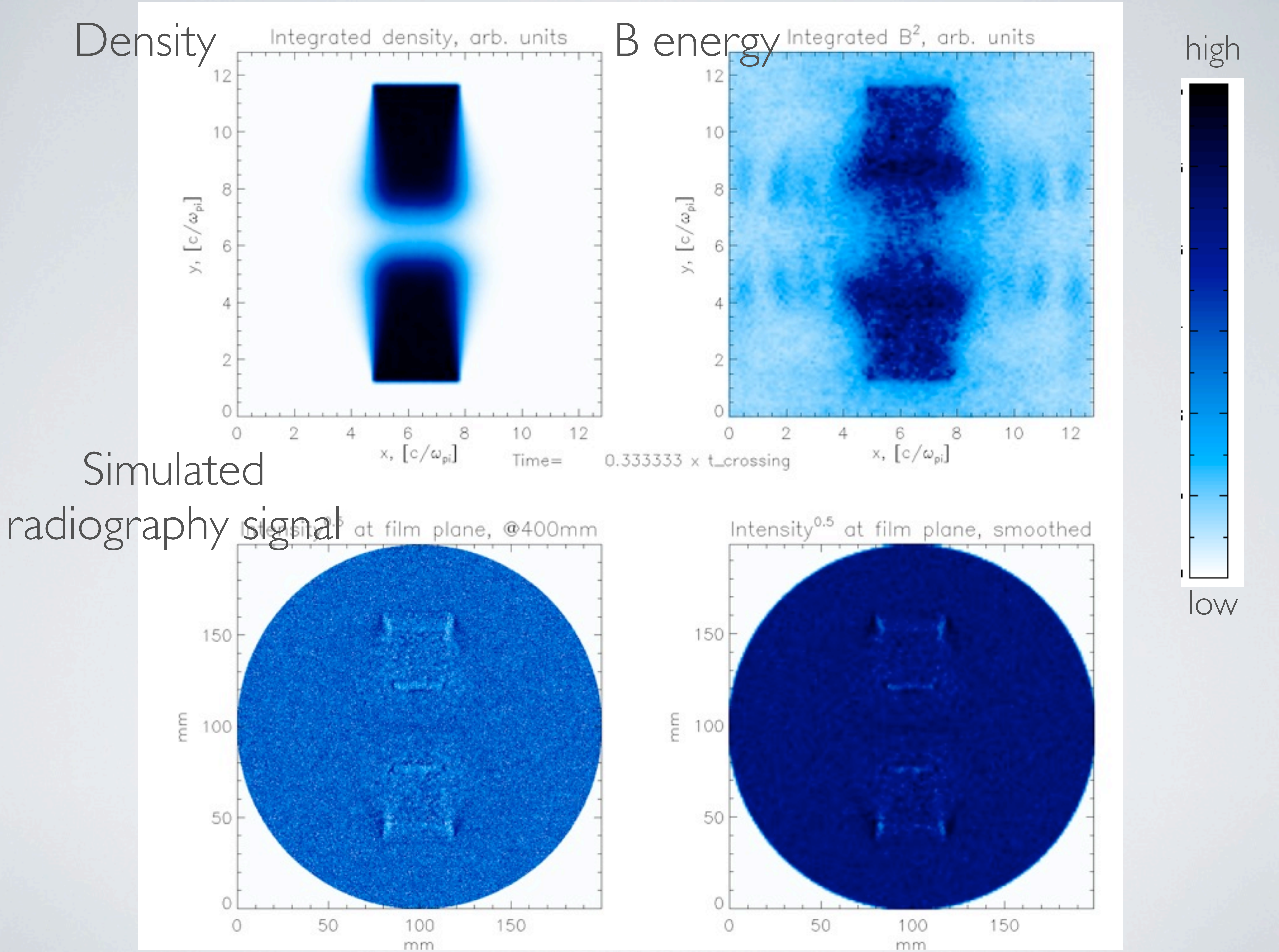
Optical Thomson scattering data provides measurements of plasma state: V, N_e, T_e, T_i

Diagnostics ii): Proton radiography

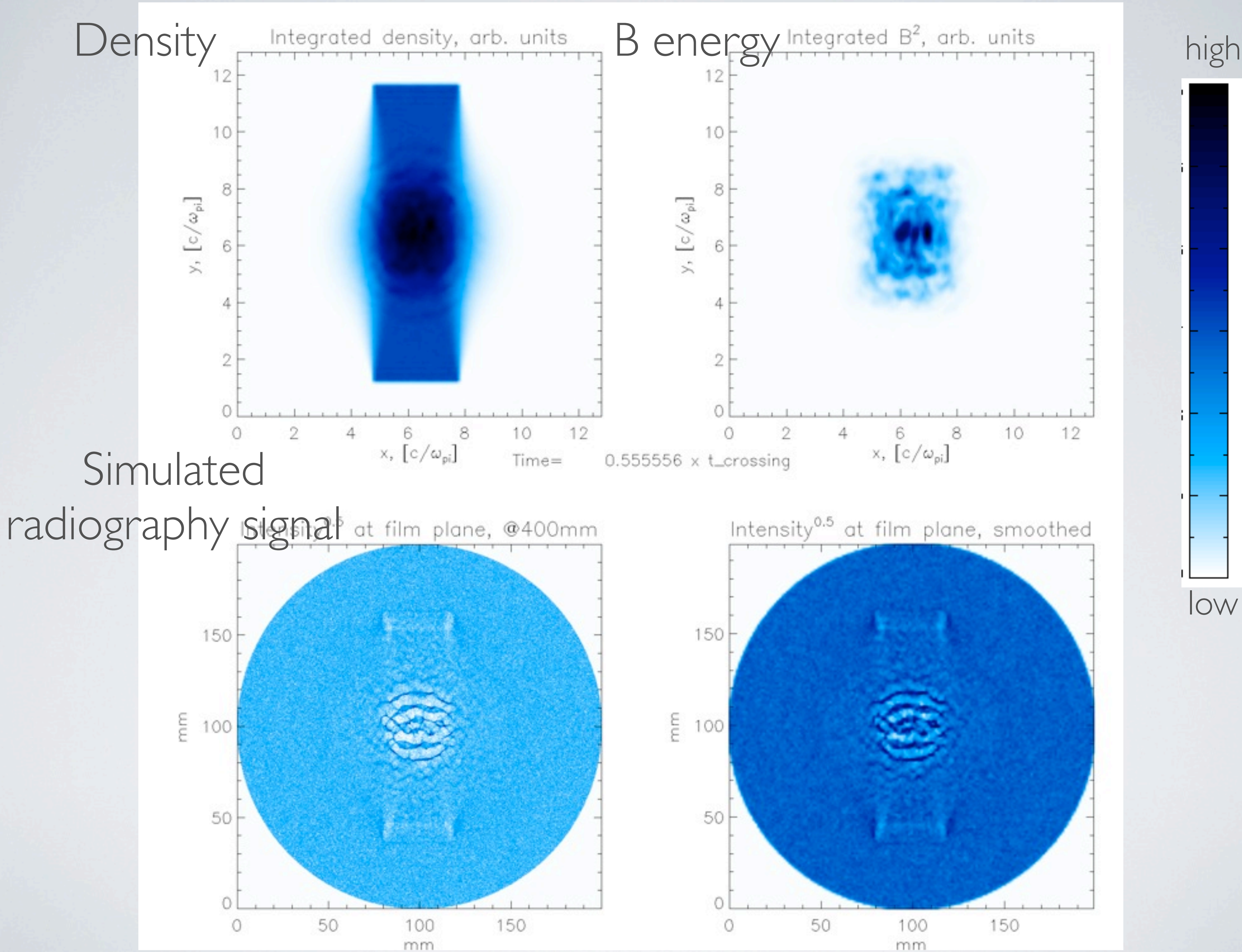
Proton detector

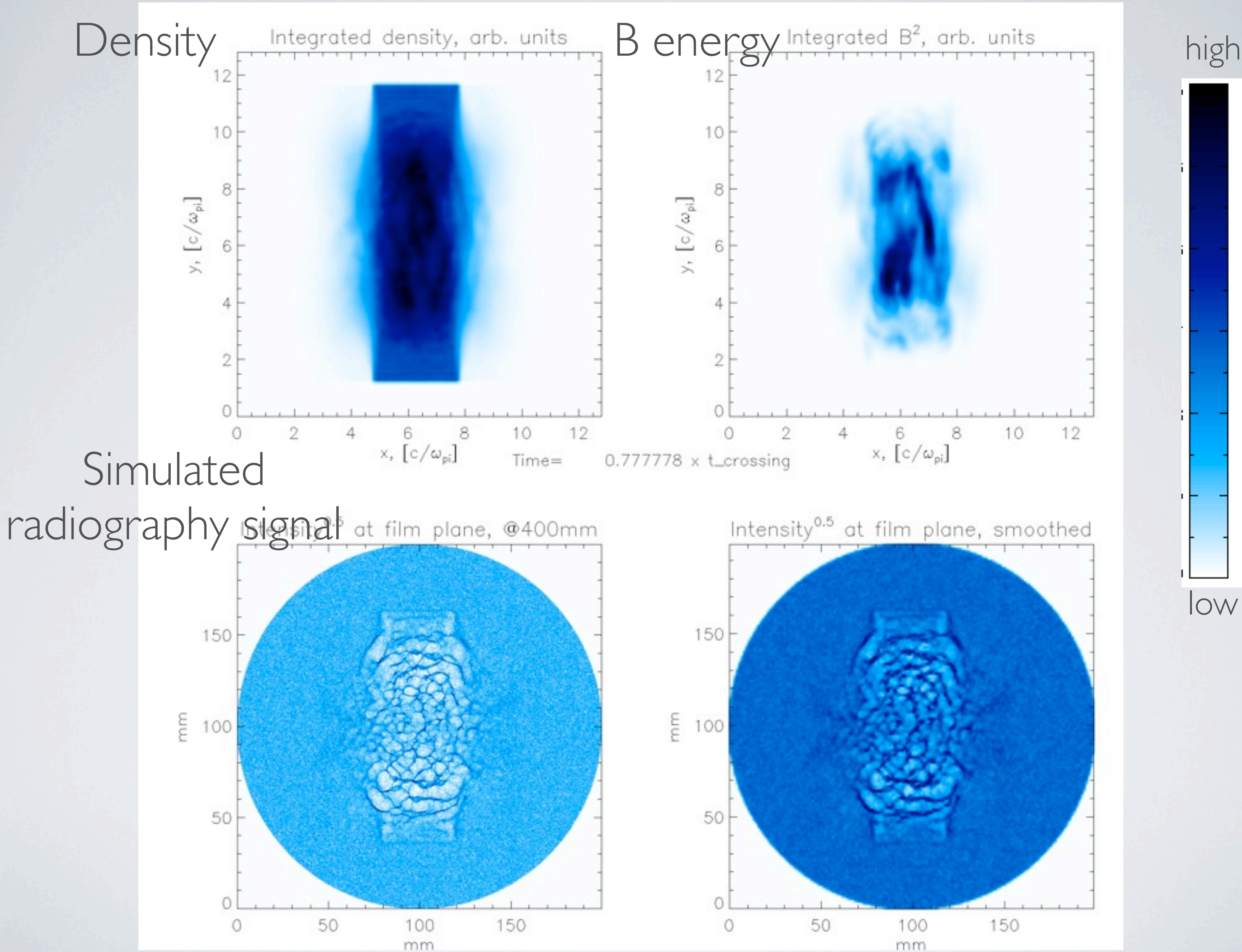


Proton source (EP laser in Omega/EP joint shots or DHe3 capsule)

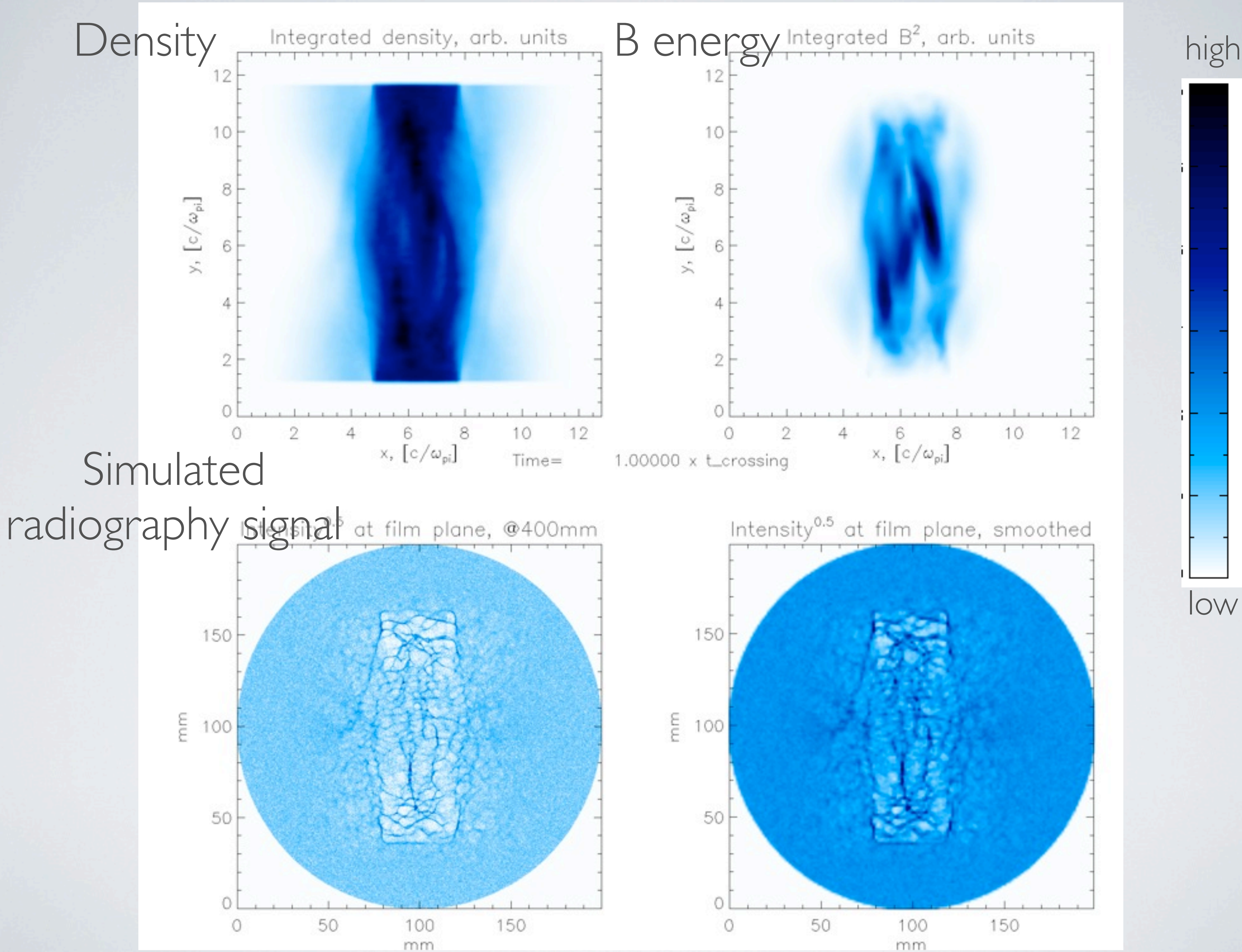


Density
Integrated density, arb. units
B energy
Integrated B², arb. units
high
low
y, [c/ω_pi]
x, [c/ω_pi]
Time= 0.333333 x t_crossing
Simulated radiography signal
Intensity^0.5 at film plane, @400mm
Intensity^0.5 at film plane, smoothed
mm
0
2
4
6
8
10
12
50
100
150

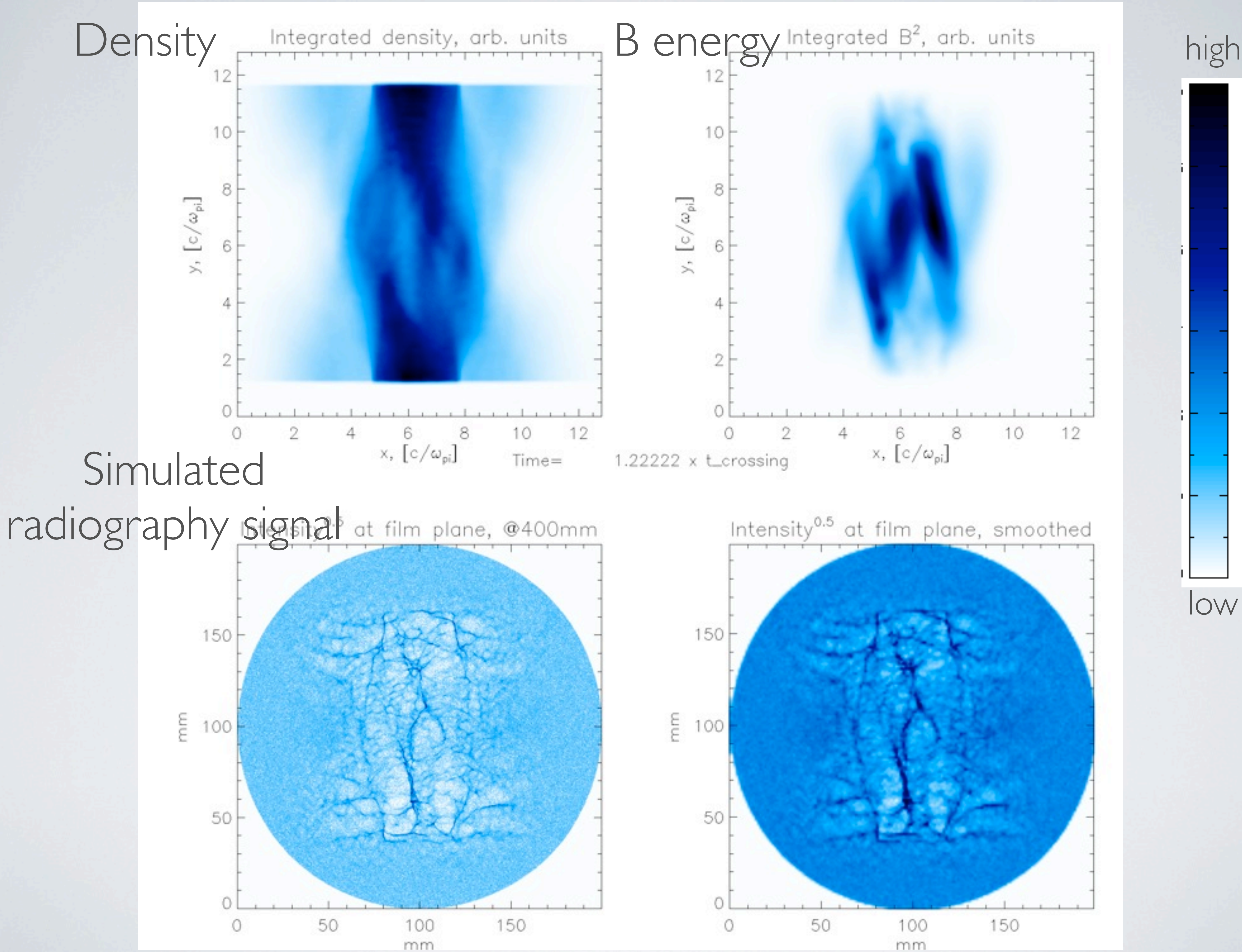

Density
Integrated density, arb. units
B energy
Integrated B², arb. units
high
low
y, [c/ω_pi]
x, [c/ω_pi]
Time= 0.555556 x t_crossing
Simulated radiography signal
Intensity^0.5 at film plane, @400mm
Intensity^0.5 at film plane, smoothed
mm

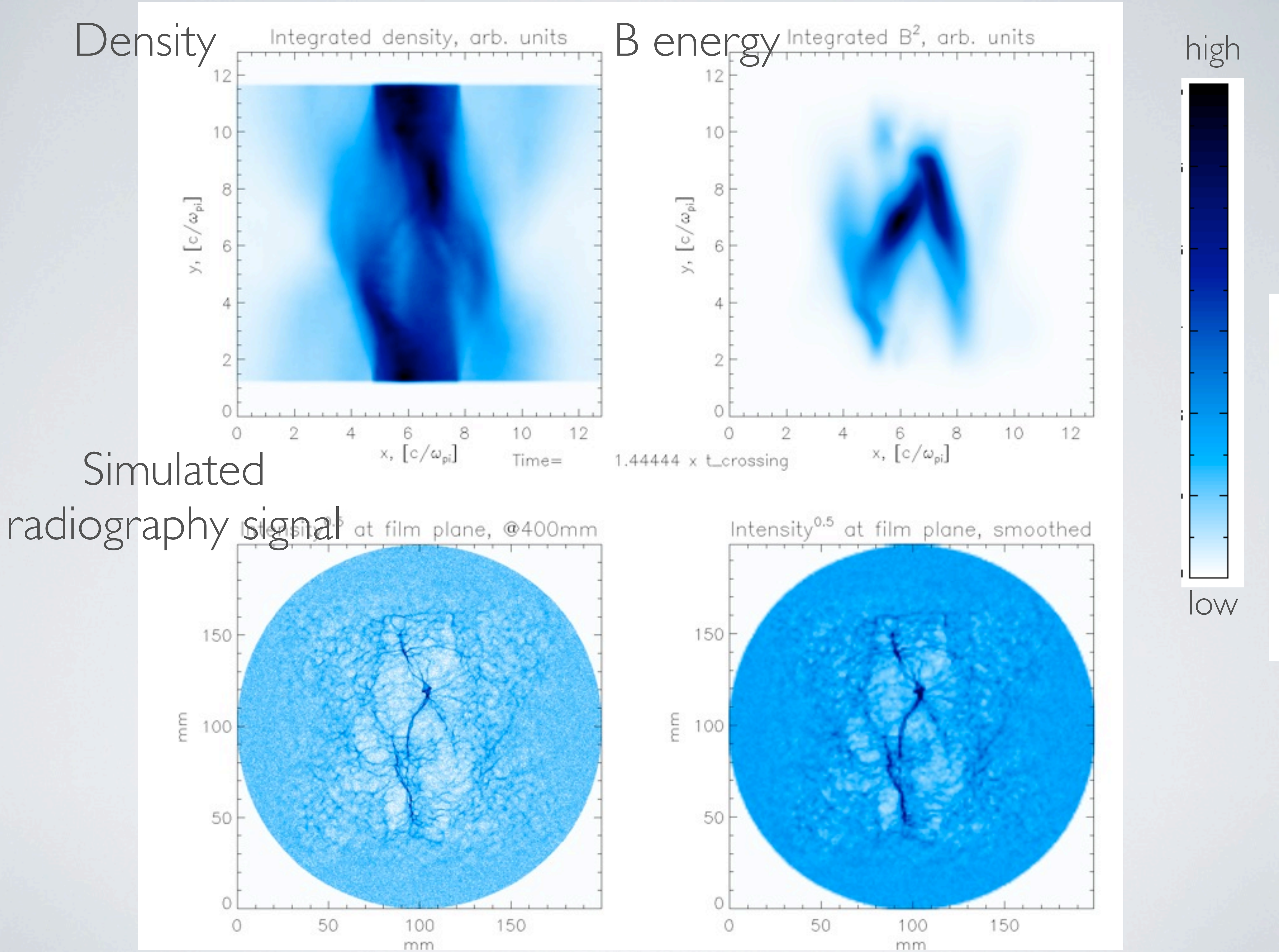


Density
Integrated density, arb. units
B energy
Integrated B², arb. units
high
low
y, [c/ωpi]
x, [c/ωpi]
Time= 0.777778 x t_crossing
Simulated radiography signal
Intensity^0.5 at film plane, @400mm
Intensity^0.5 at film plane, smoothed
mm



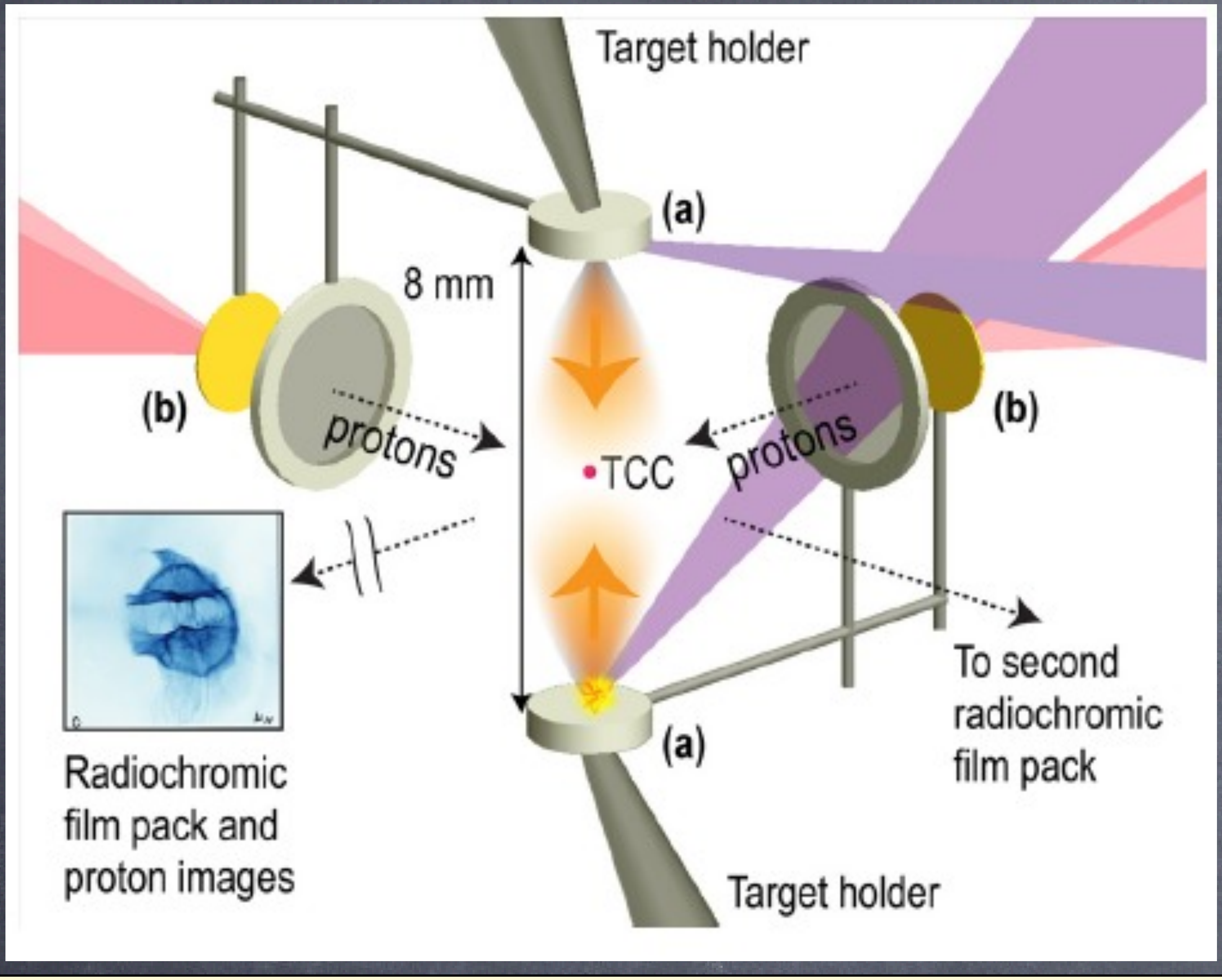
Density
Integrated density, arb. units
B energy
Integrated B², arb. units
high
low
y, [c/ωpi]
x, [c/ωpi]
Time= 1.00000 x t_crossing
Simulated radiography signal
Intensity^0.5 at film plane, @400mm
Intensity^0.5 at film plane, smoothed
mm

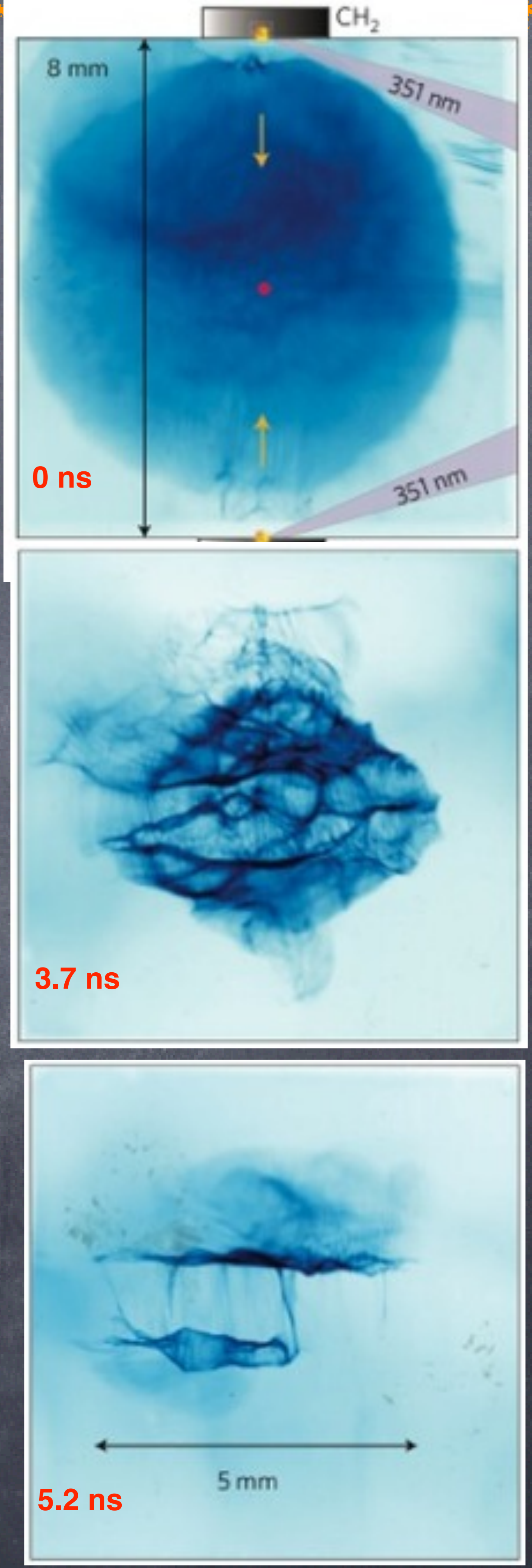

Density
Integrated density, arb. units
B energy
Integrated B², arb. units
high
low
y, [c/ω_pi]
x, [c/ω_pi]
Time= 1.22222 x t_crossing
Simulated radiography signal
Intensity^0.5 at film plane, @400mm
Intensity^0.5 at film plane, smoothed
mm



Density
Integrated density, arb. units
B energy
Integrated B², arb. units
high
low
y, [c/ωpi]
x, [c/ωpi]
Time= 1.44444 x t_crossing
Simulated radiography signal
Intensity^0.5 at film plane, @400mm
Intensity^0.5 at film plane, smoothed
mm

Observed structures: i) transverse "pancakes"

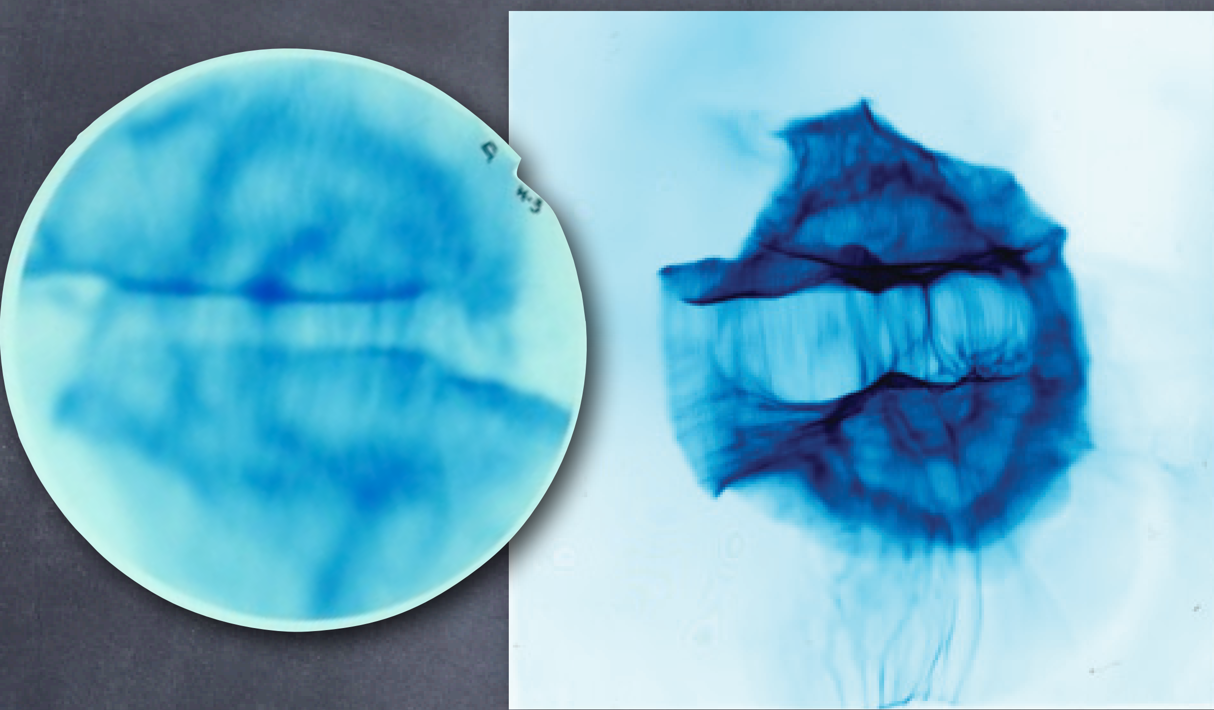




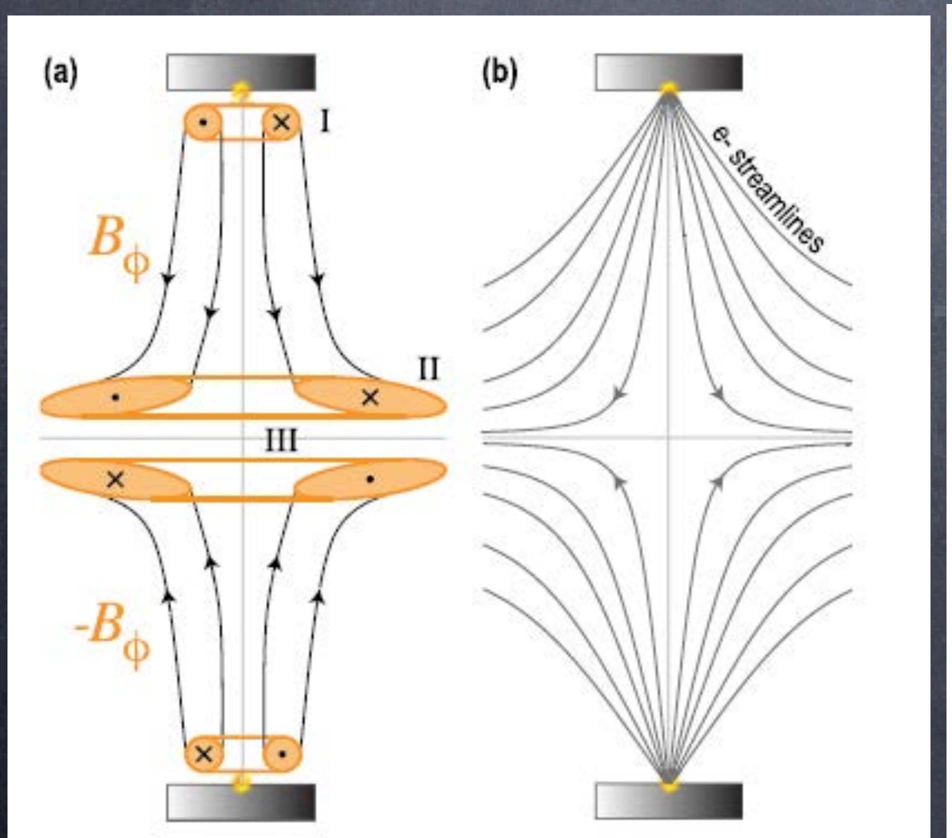
- **We have obtained visual evidence that small-scale plasma processes make macroscopic field structures (self-organization) (N. Kugland et al, Nature Physics, 2012)**
- **Magnetic field advection by the electron flow and its "stretching" near the midplane may explain this phenomenon (D. Ryutov et al., PoP, 2013)**

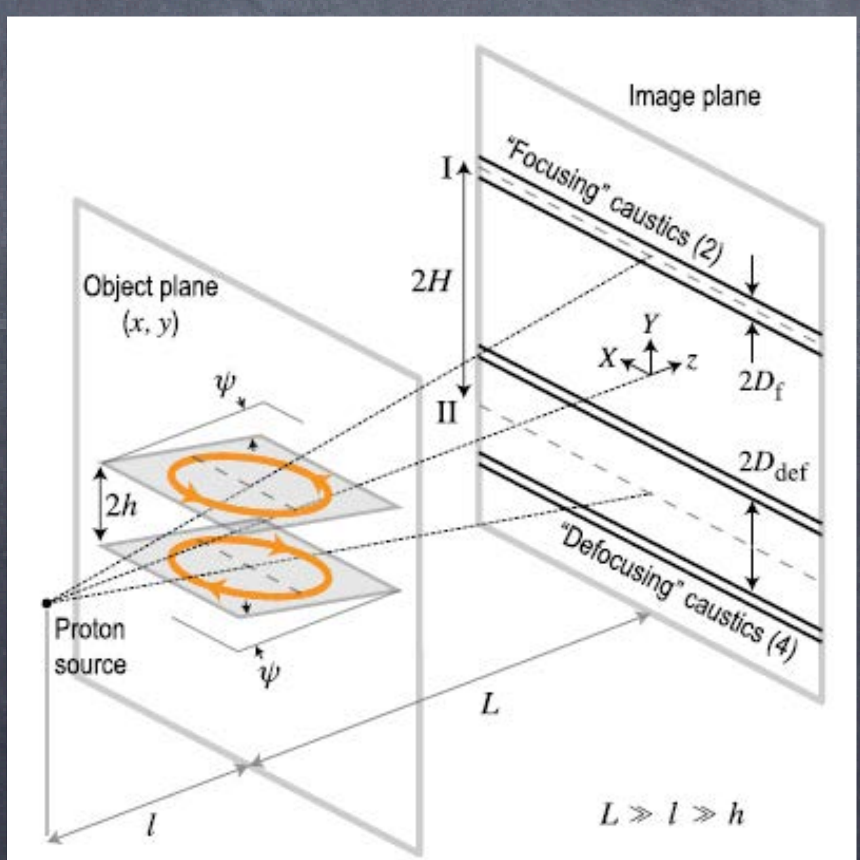
Kugland et al., Nature Physics, 2012

Observed structures: i) tranverse "pancakes"



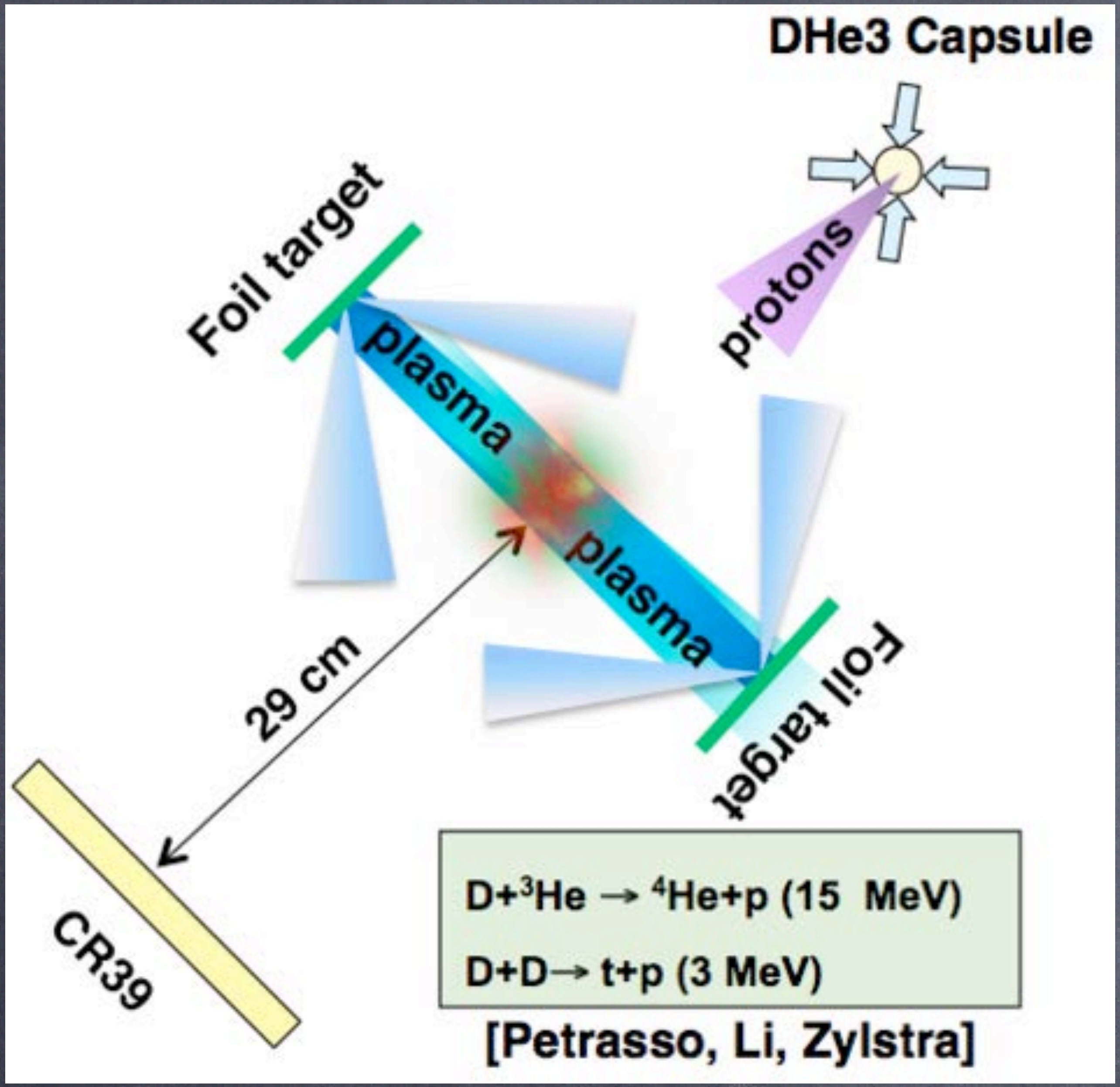
- Possibly due to B-field advection (Ryutov et al., 2013)
- Produced by the interaction of interpenetrating streams with large-scale fields, either introduced by external coils or generated in the plasma near the laser targets (Biermann battery).

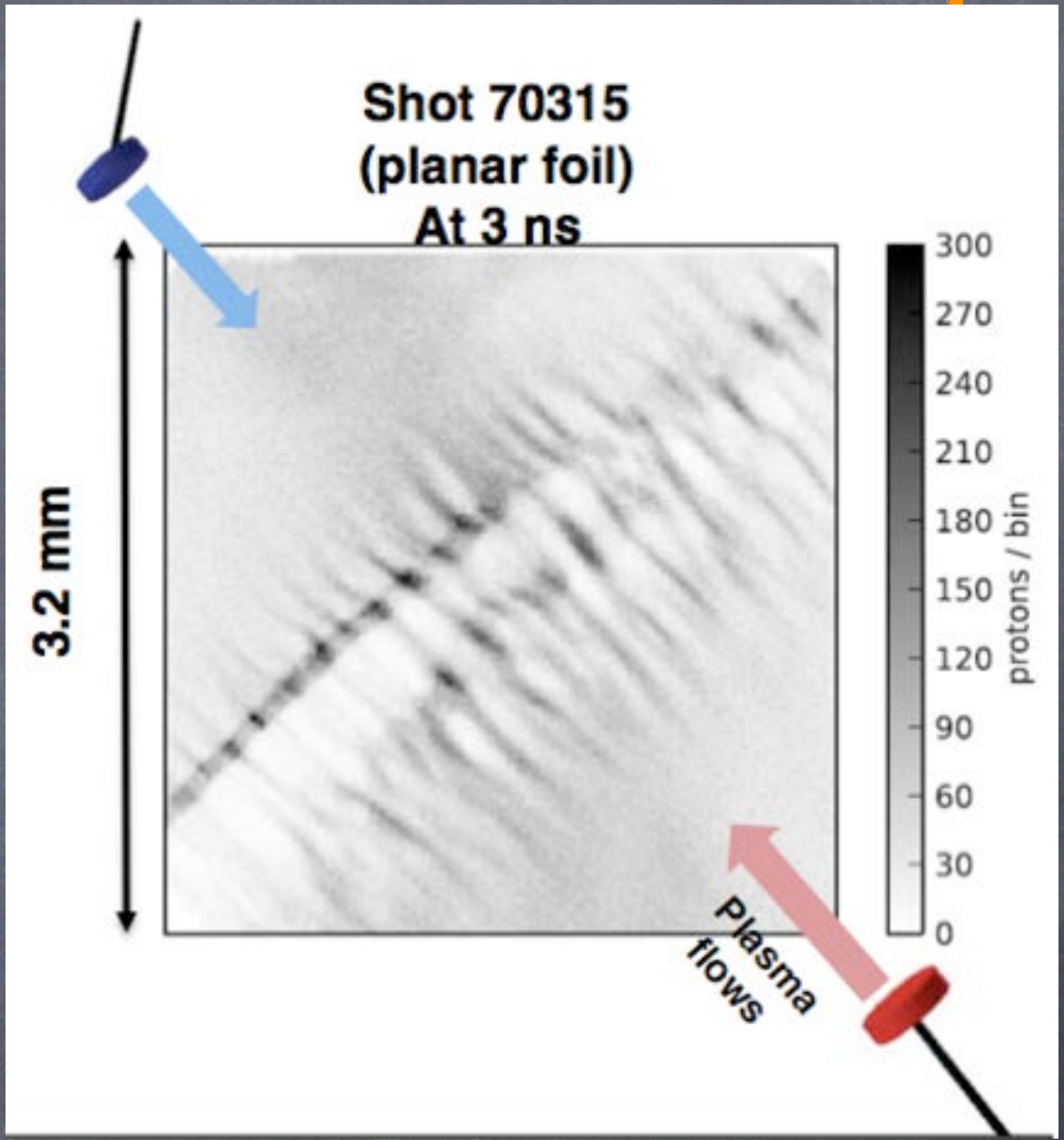




- Seed field is from Biermann battery near target surface in toroidal shape
- Counterstreaming flows advect and recompress this field near the midplane

Observed structures: ii) filamentation

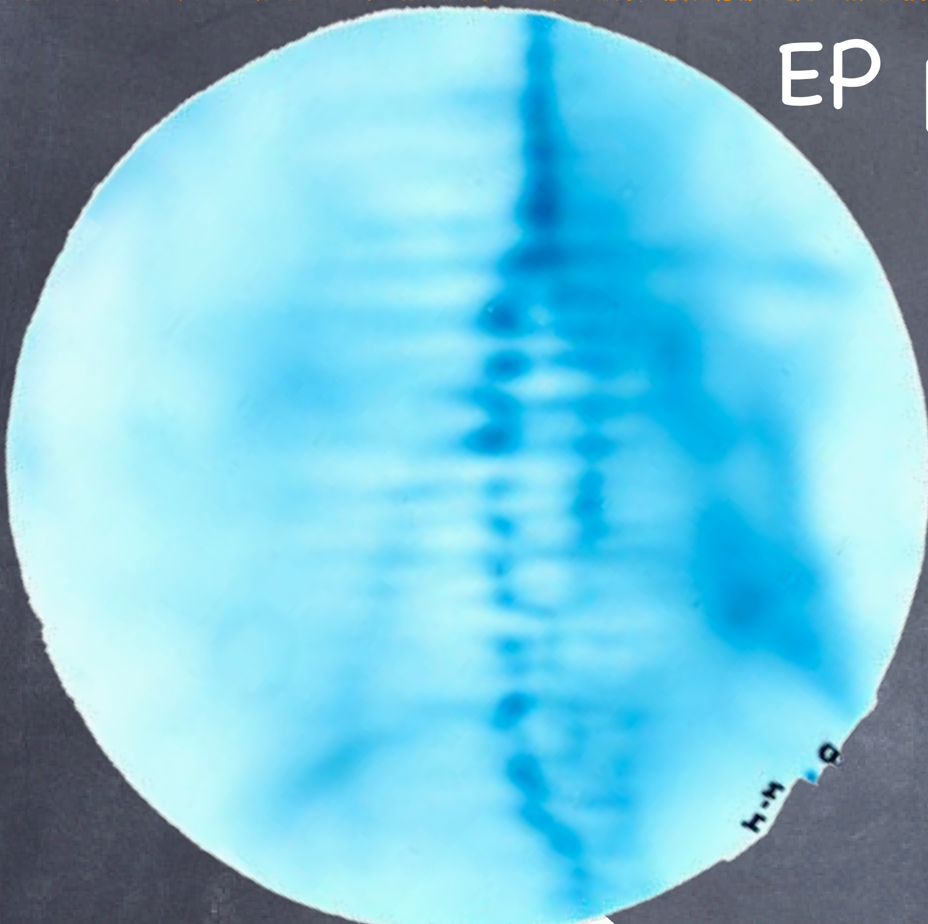


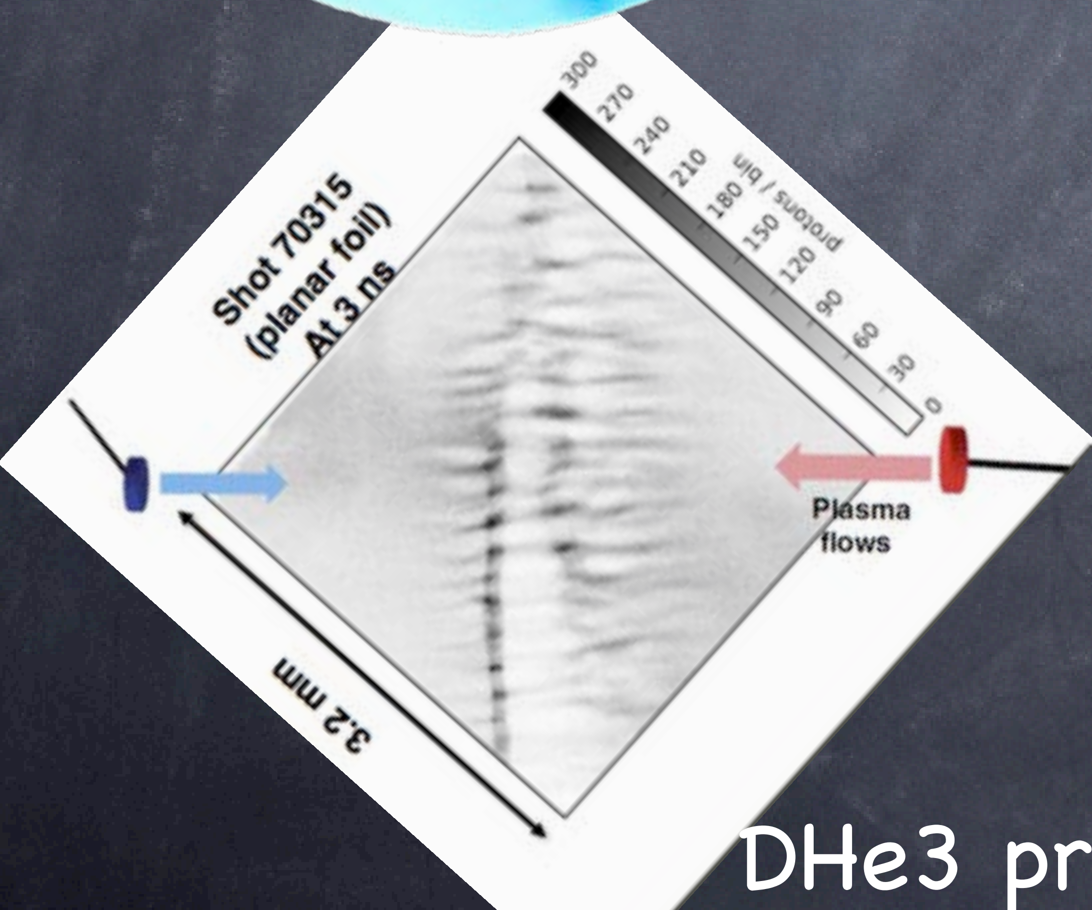


- First clearly seen filamentation from DHe3 capsule implosion protons. Later confirmed that same filamentation is seen with EP protons on Omega
- Direct observation of Weibel instability (Huntington et al 2013)

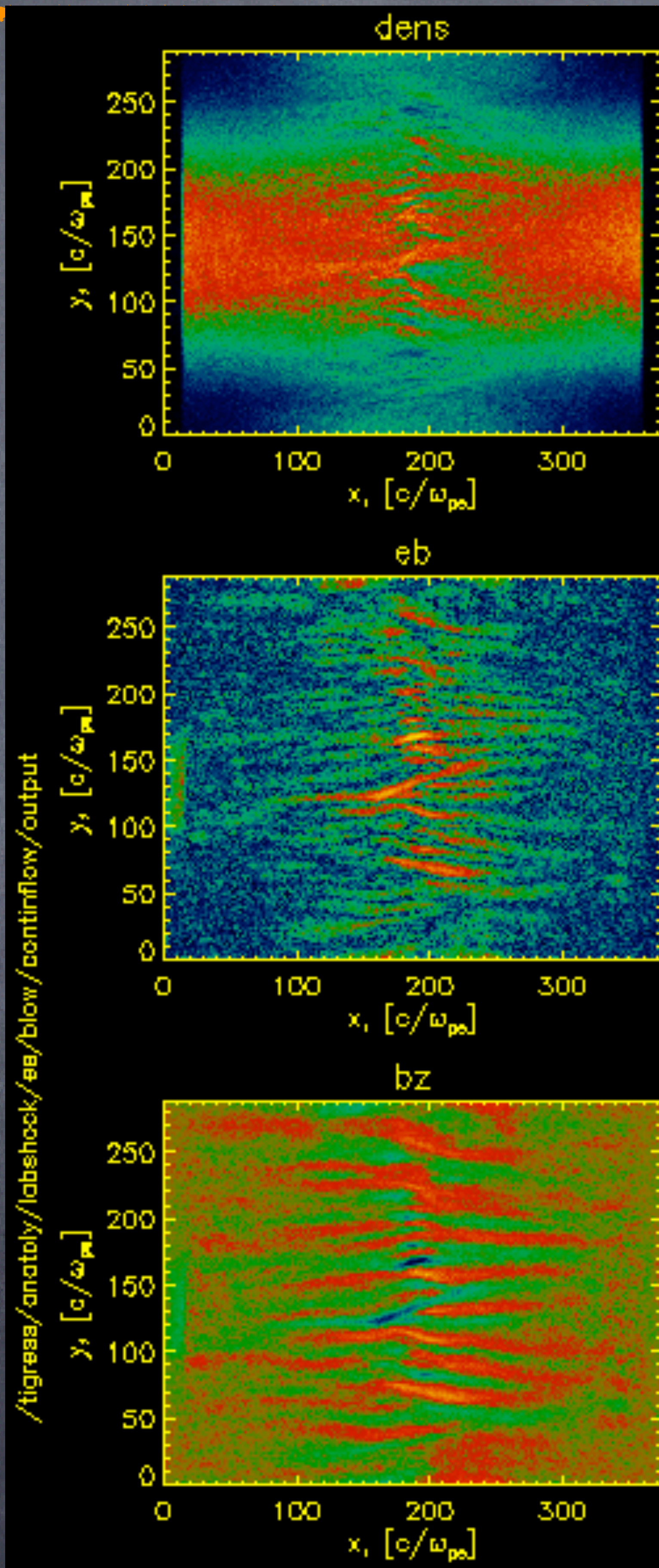
Observed structures: ii) Filamentation

EP protons





DHe3 protons



Density

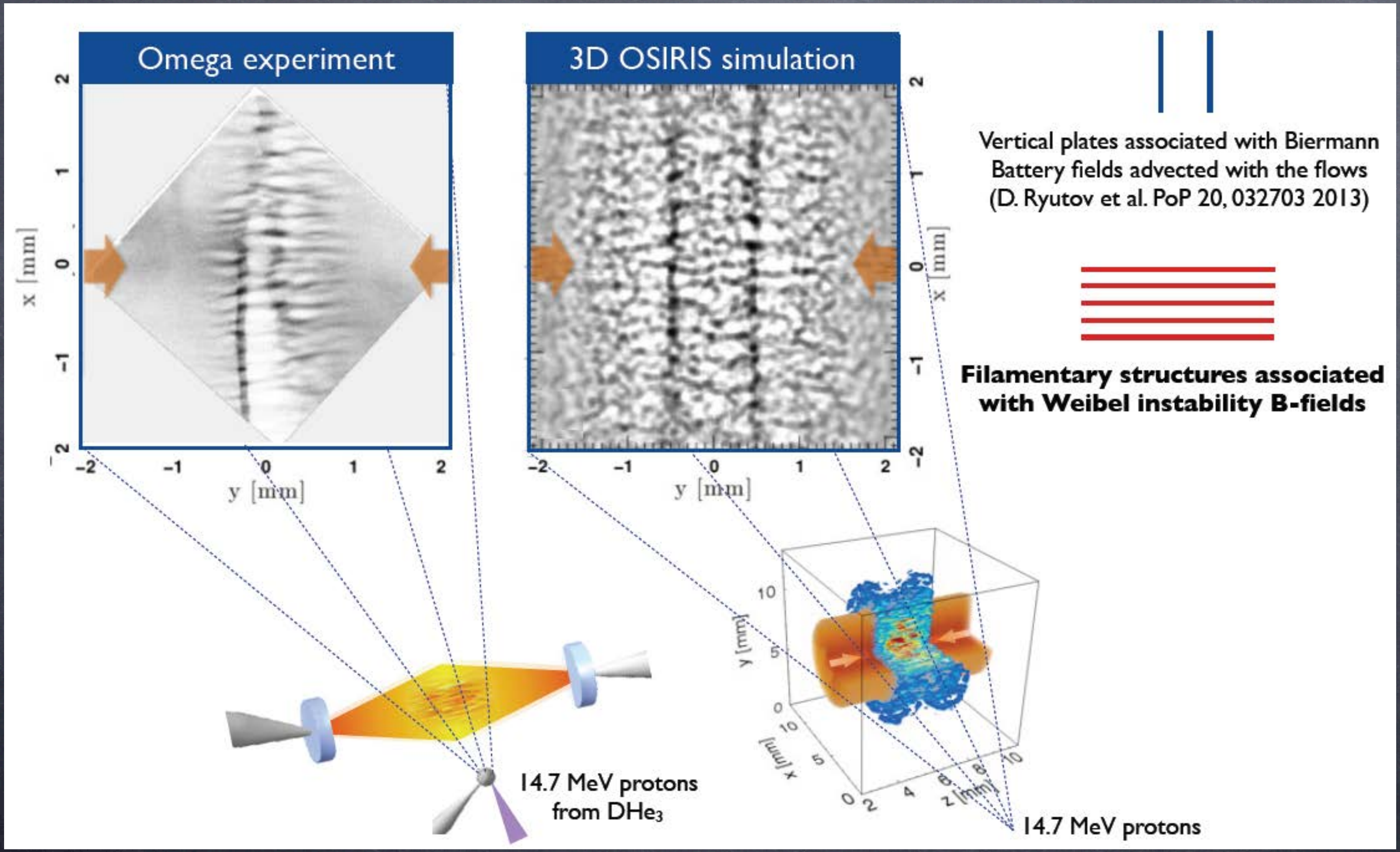
$\omega_{pe}t$=2250

B^2

Simulation includes Biermann fields (J. Park, AS)

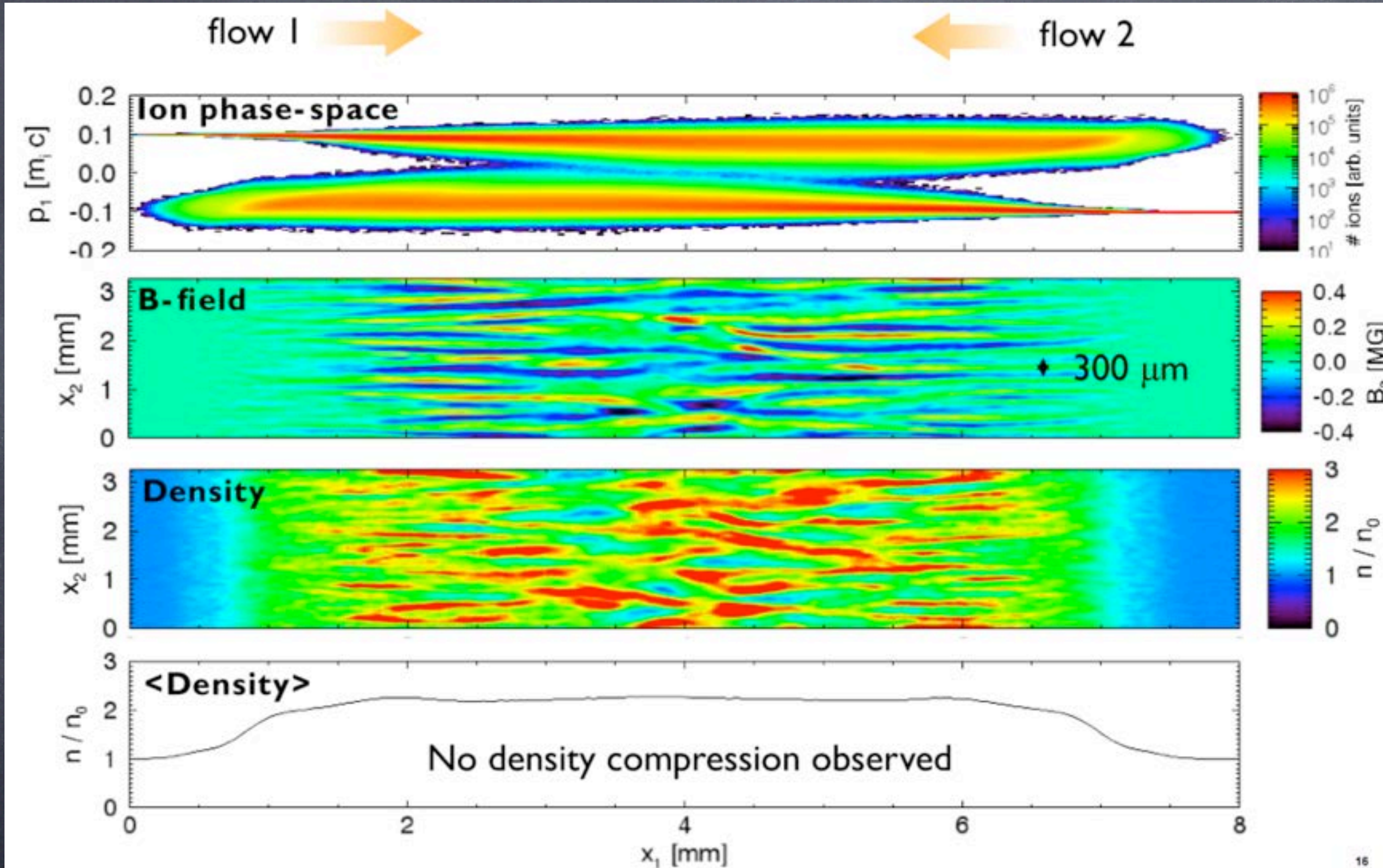
B

Weibel Instability is directly observed @ Omega



C. Huntington, F. Fiuza, J. Ross, A. Zylstra, et al. (2013)

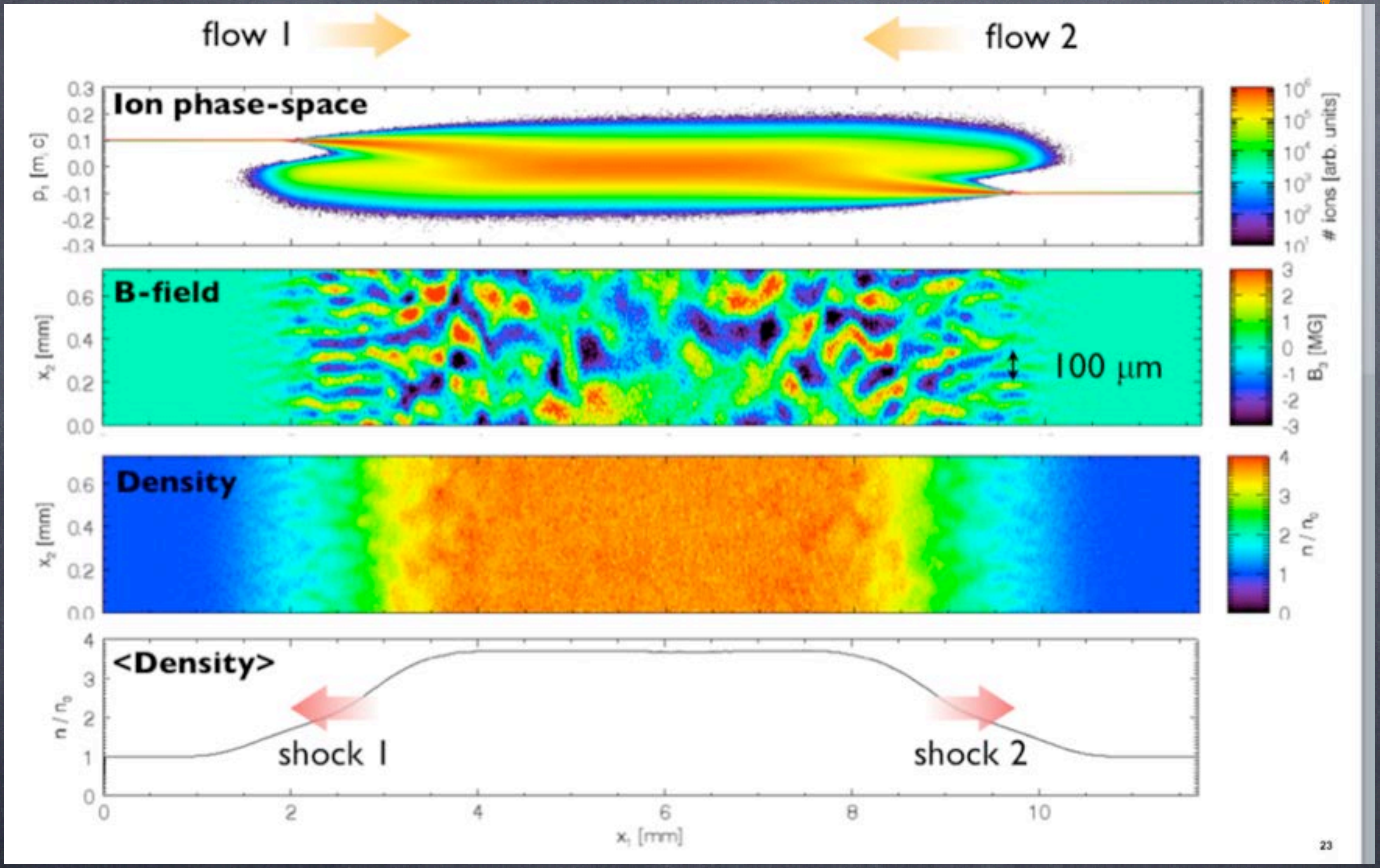
No shock expected for Omega conditions



OSIRIS simulation (Fiuza)

Interaction distance is too short (<300 ion skin depths) to fully form a shock. However, we see initial instability.

Shocks will be formed on NIF



OSIRIS simulation (Fiuza)

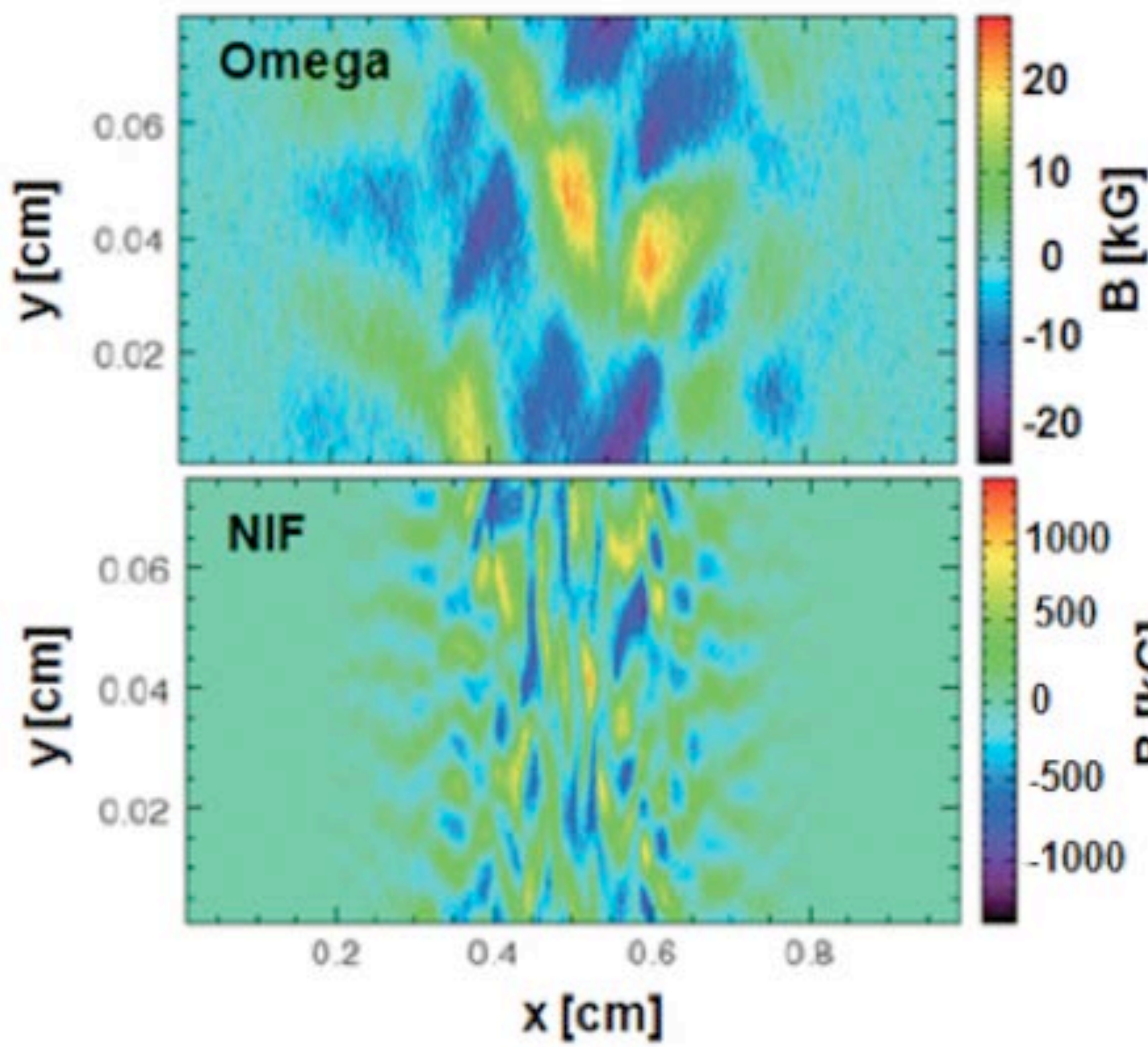
Higher density allows to have > 300 ion skin depths between targets.

Requirements for NIF experiment

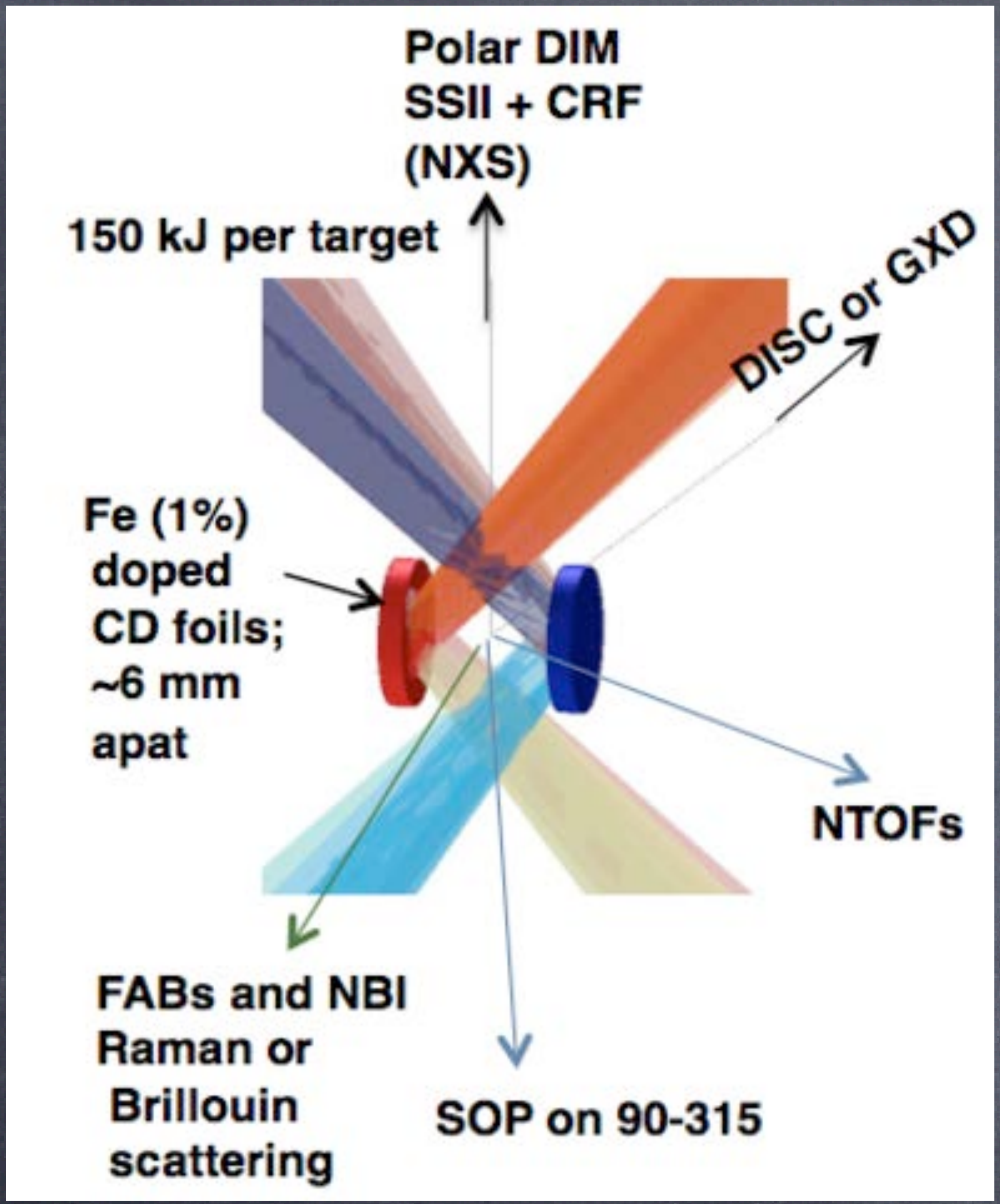
NIF is the only facility that can create a large plasma with all of these properties:

- **High density** $N_e > 10^{20}$ cm^{-3} (well-formed shock, short ion skin depth)
- **High flow velocity** > 2000 km/s (collisionless)
- **High temperature** $T_e > 1$ keV (High magnetic Reynolds # $R_M >> 1000$ and weak intra-stream collisions)

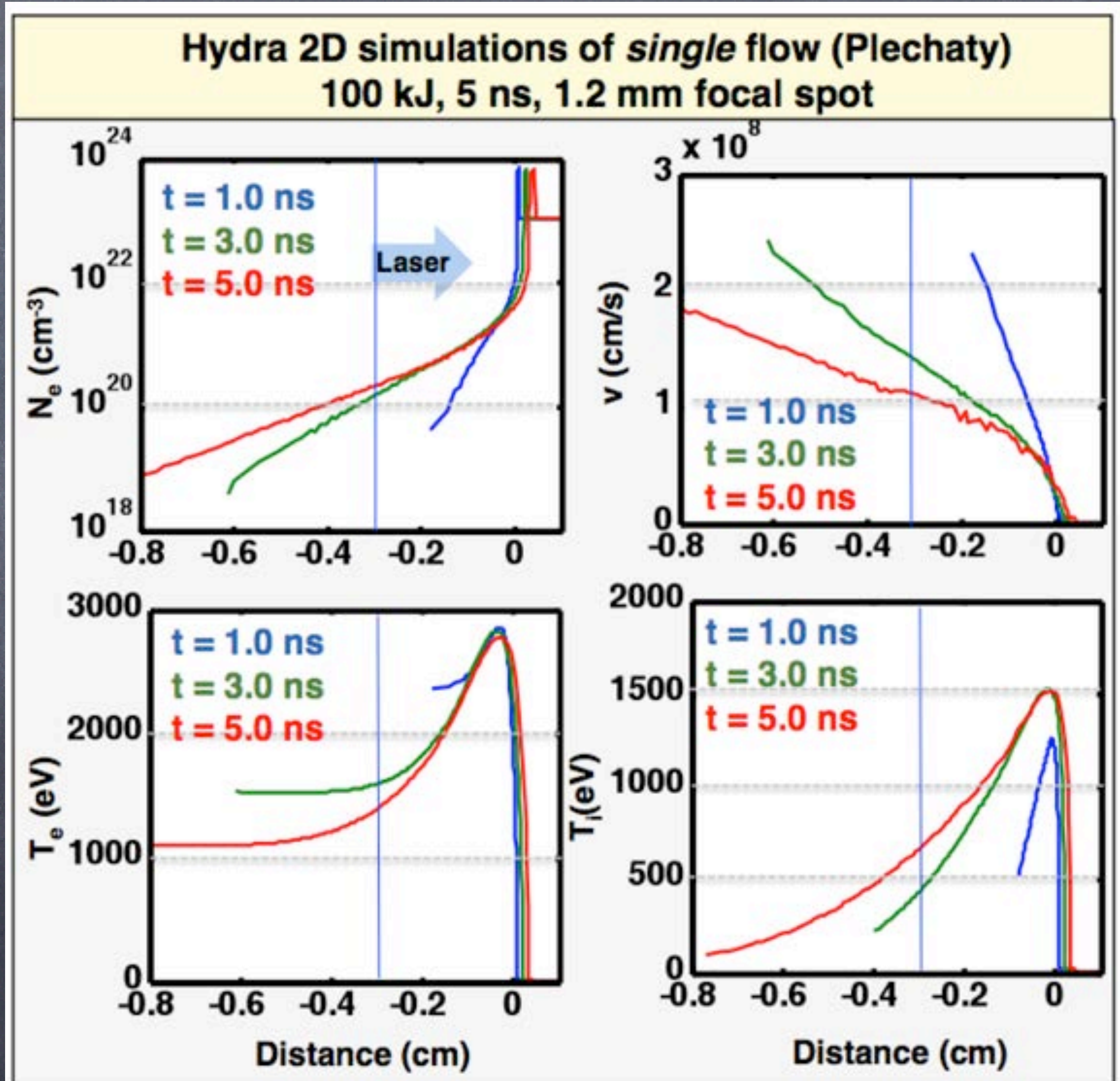
PIC simulation predicts fully formed shocks and detectable magnetic fields



Design of collisionless shock experiment on NIF

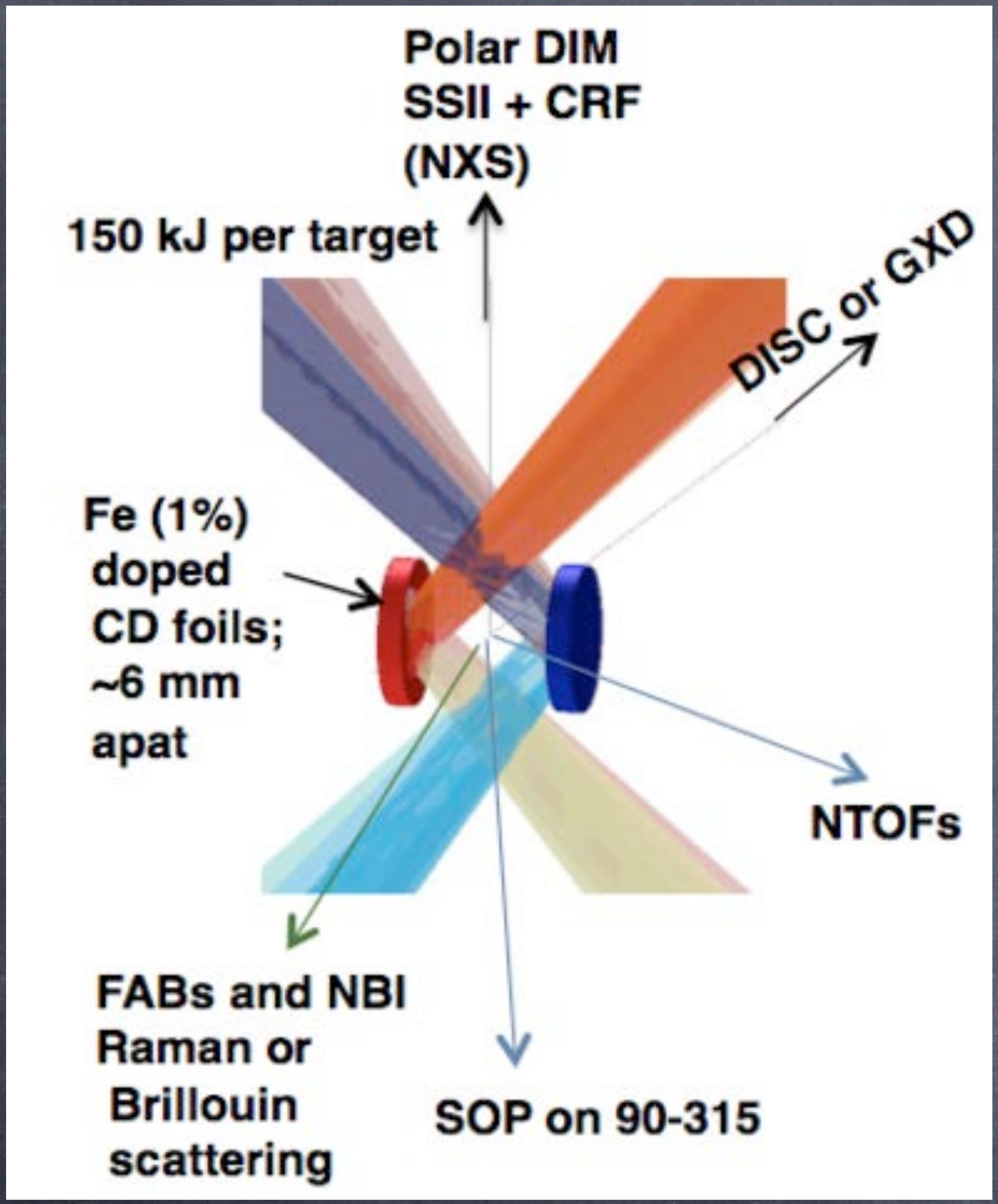


First experiment: determine plasma state with NIF diagnostics



Rad-hydro simulations predict: Te>1keV, Ne>10^{20}cc. This gives high Rm>10000, for single flow. For double flow, expect Te of several keV.

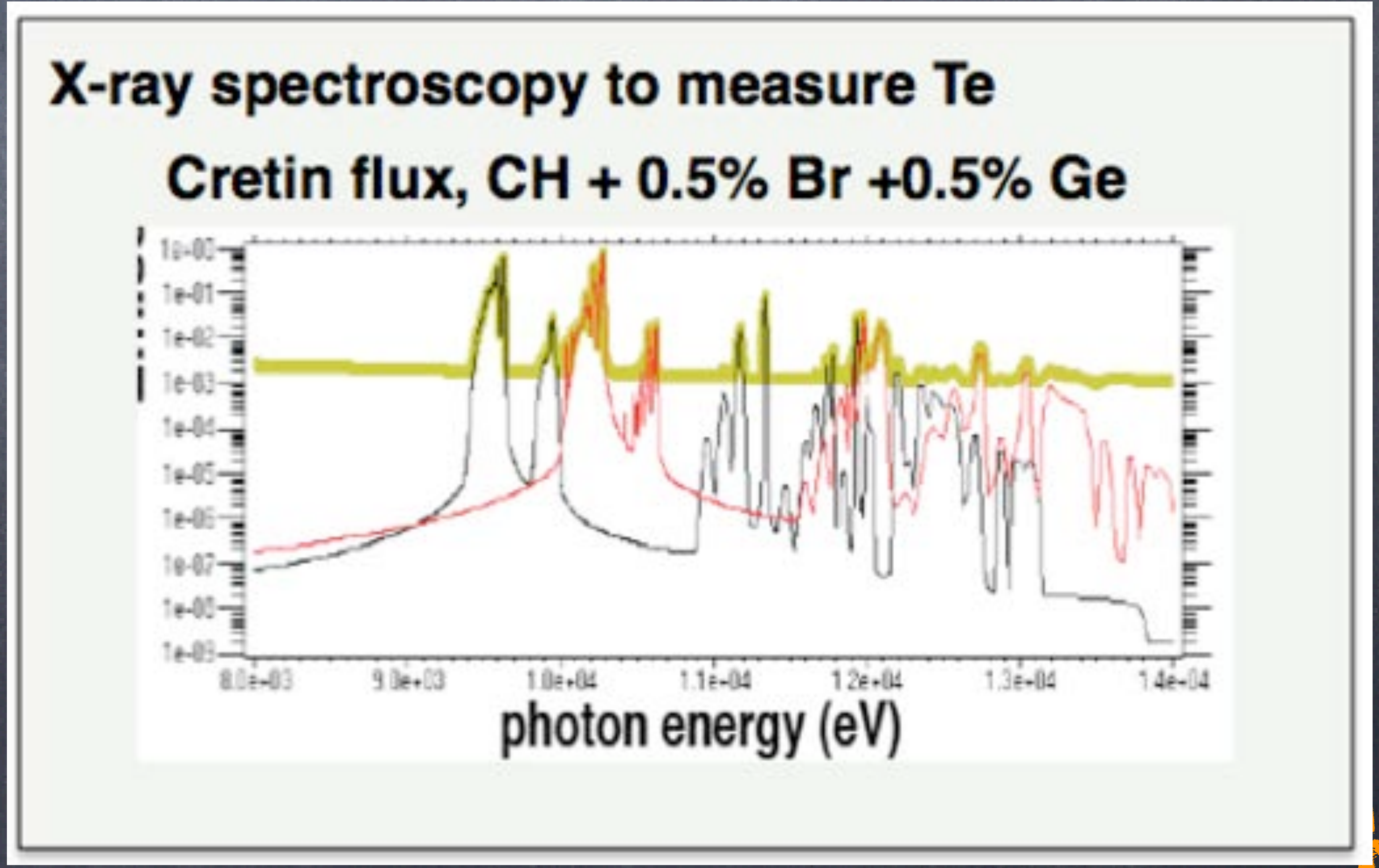
Design of collisionless shock experiment on NIF



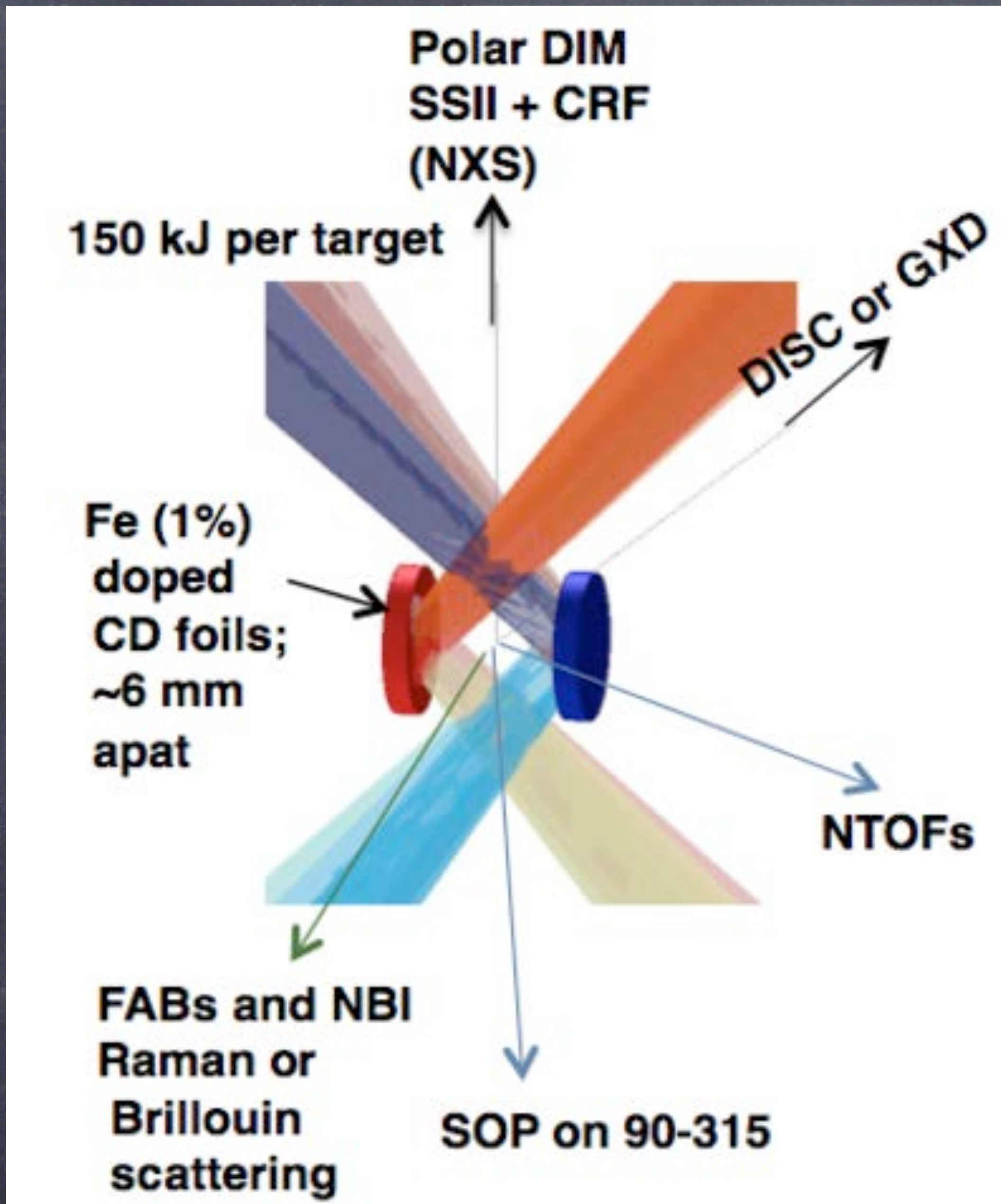
First experiment: determine plasma state with NIF diagnostics

Deuterated targets: TOF neutronics to measure Yn and Tion

Doped targets: measure X-ray spectrum



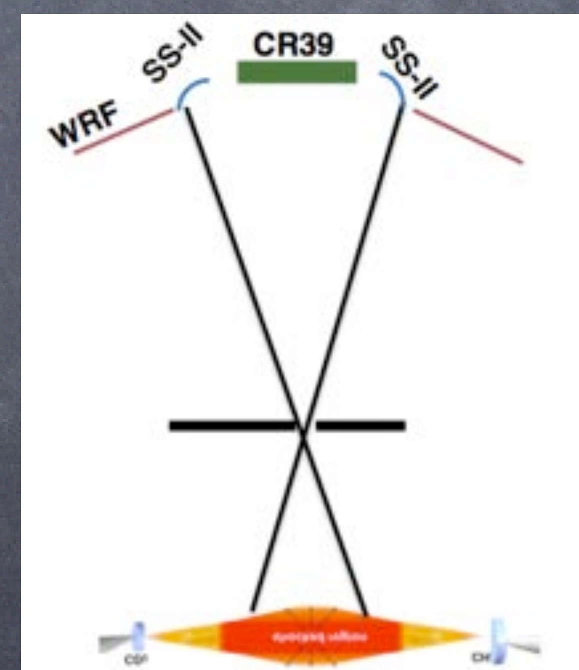
Design of collisionless shock experiment on NIF



First experiment: determine plasma state with NIF diagnostics

Hot plasma -- bremsstrahlung self-emission (streaked X-ray & optical imaging)

Pinhole proton imaging with CR39



- D+D→ T + p
- D+D→ ^{3}He + n

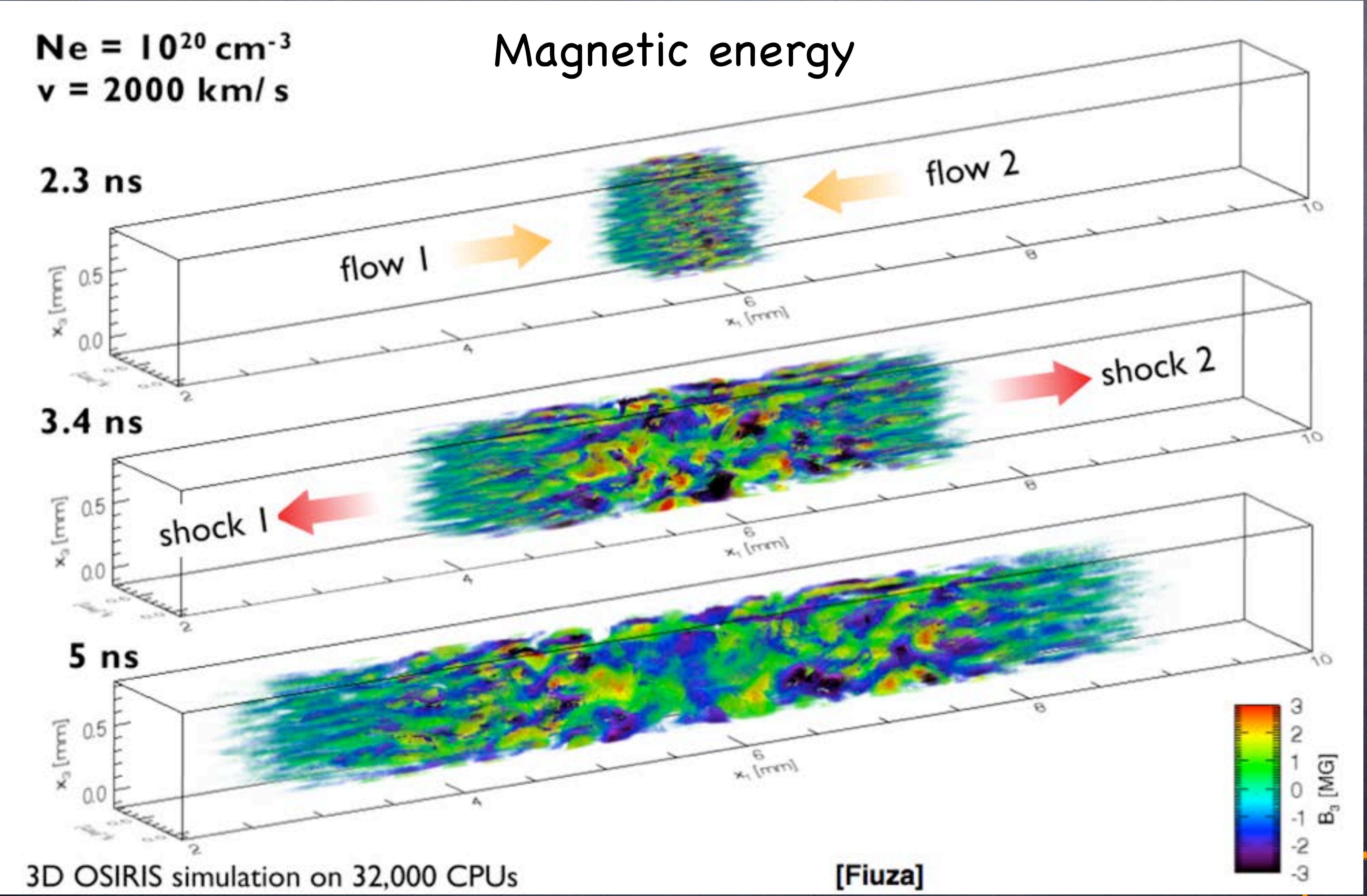
FABS and NBI -- Raman and Brillouin backscattering to get plasma conditions

Diagnostic summary

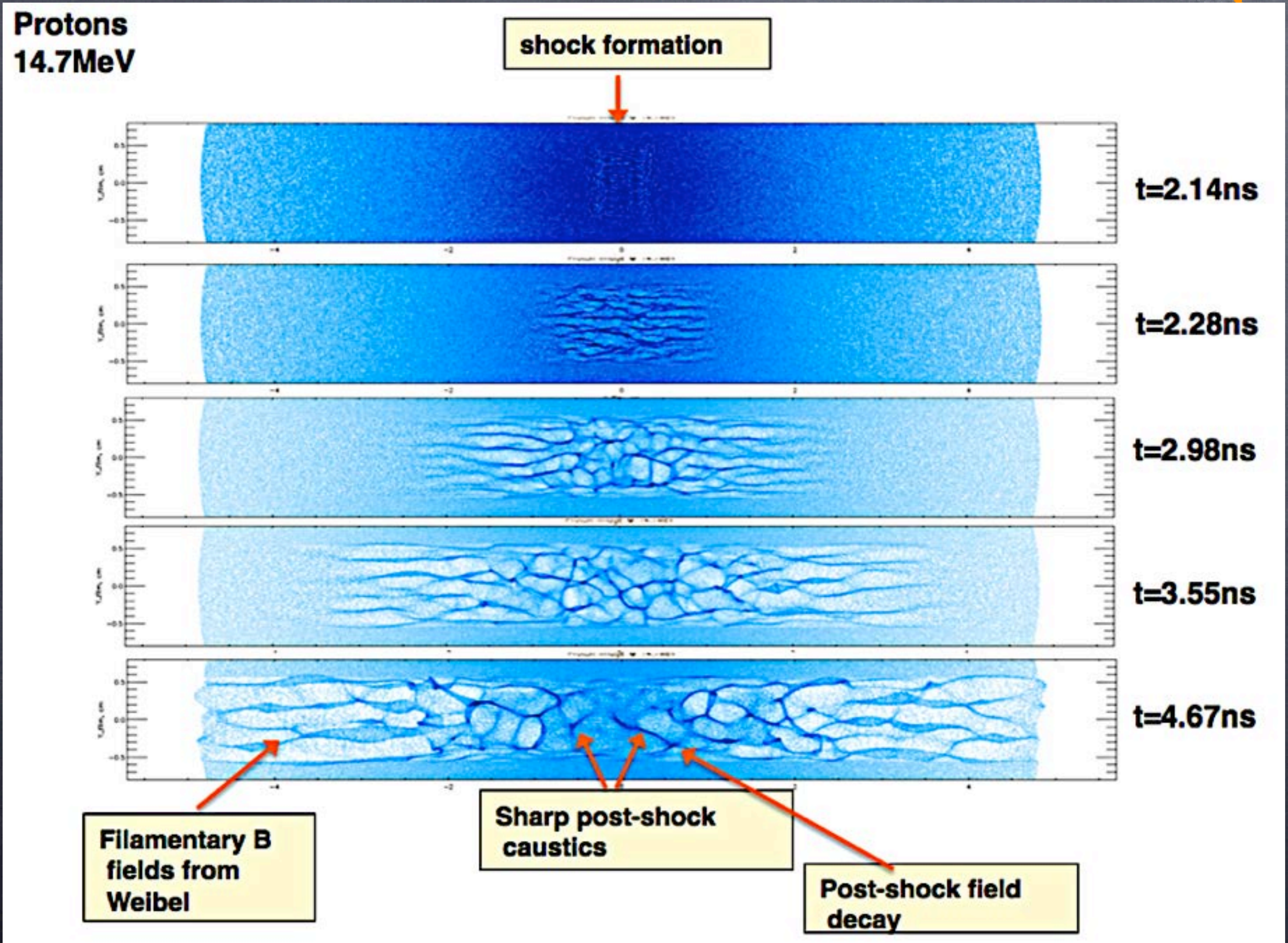
Measure	Purpose	Diagnostics (Omega)	Diagnostics (NIF)
Plasma state	Measure plasma parameters of V, Te, Ti, Ne	• Thomson scattering	• X-ray spectrometer • SRS backscatter
Shock imaging	Visualize shock formation	• Proton probe	• X-ray streak camera (self-plasma emission) • proton self-emission
Magnetic field measurements	Weak magnetic field	• Proton probe	• None (until DHe3 or ARC backlighter)
External magnetic field	Magnetized	• MIFEDS	• None
Shock	Shock forming confirmation		• Neutron yield from CD/CD foil CD/CH foil
Simulation	• Rad-hydro for laser/target interaction • PIC simulation for Weibel		

First experiment -- no B field probe (protons).
Development of DHe3 system is very needed.

Proton Radiogrpahy of shock development on NIF



Proton Radiogrpahy of shock development on NIF



Conclusions

- Through simulations we understand the regimes of shock formation and the necessary conditions to create shocks in colliding plasmas.
- Collisionless conditions relevant for astrophysical scaling are now accessible at HED laser facilities. Diagnostics work well.
- Detection of filamentary features in the radiography signal: first signatures of collisionless shock mediation and Weibel instability. Fully formed electromagnetic shock is expected at larger interaction lengths or higher densities (will be accessible at NIF).
- Particle acceleration will be possible to begin addressing when we conclusively form a shock. Of most interest is the dynamics of first shock crossing.
- Reproducibility and control over the conditions will ultimately be most beneficial for elucidating the physics of shocks.
- NIF will be a strong platform for collisionless plasma physcs research.
- Wishlist for NIF: Thomson scattering, diagnostic protons from DHe3 (or ARC) and MIFEDS system.